Soil Parameter Testing System

Dissertation submitted to
Visvesvaraya National Institute of Technology, Nagpur
In partial fulfillment of the requirements for the award of the degree

Master of Technology
in
VLSI Design

By

Aayush Tamrakar
(MT23MVD003)

Under the guidance of

Dr. Ganesh C. Patil

Centre for VLSI and Nanotechnology
Visvesvaraya National Institute of Technology
Nagpur 440010 (India)

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Visvesvaraya National Institute of Technology, Nagpur

DECLARATION

I, **Aayush Tamrakar**, hereby declare that this dissertation titled **"Soil Parameter Testing System"** is carried out by me in the **Center for VLSI and Nanotechnology** of Visvesvaraya National Institute of Technology, Nagpur. The work is original and has not been submitted earlier whole or in part for the award of any degree/diploma at this or any other Institution / University.

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This is to certify that the dissertation titled **"Soil Parameter Testing System"** is submitted by **Aayush Tamrakar (MT23MVD003)** in partial fulfillment of the requirements for the award of **Master of Technology in VLSI Design,** VNIT Nagpur. The work is comprehensive, complete and fit for final evaluation.

Dr. Ganesh C. Patil
Centre for VLSI and Nanotechnology
VNIT, Nagpur.

Prof. Sanjay B. Dhok
Head, Centre for VLSI and Technology
VNIT, Nagpur
Date:_____

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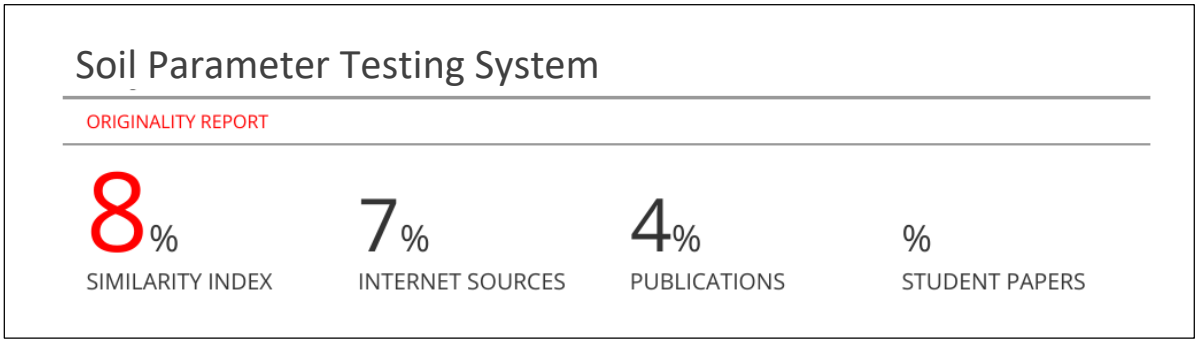

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Supervisor

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Abstract

This thesis presents the Soil Parameter Testing System, an advanced IoT-based platform developed to address the evolving demands of precision agriculture. Traditional soil assessment techniques—often manual, periodic, and labor-intensive—struggle to provide the real-time, high-resolution data needed for modern, resource-efficient farming. To overcome these limitations, the system integrates multiple sensors, including temperature, humidity, soil moisture, and pH, all managed by a versatile ESP32 microcontroller. Data from both analog and digital sensors are processed and transmitted wirelessly using a SIM800L GSM module, allowing for seamless remote monitoring and cloud-based analysis.

The methodology emphasizes energy efficiency through optimized sensor duty cycles and deep sleep operation, enabling the device to function autonomously in the field. Power is supplied by a solar-charged 2000 mAh Li-ion battery, ensuring continuous operation even in off-grid environments. Rigorous calibration and system validation confirm that the Soil Parameter Testing System delivers accurate, reliable measurements over extended periods. Field trials demonstrate its ability to maintain stable performance, provide actionable insights, and support scalable deployment across diverse agricultural settings.

The modular design facilitates easy integration of additional sensors or communication modules, making the system adaptable to a wide range of crops and environmental conditions. By providing real-time, actionable data on key soil parameters, the platform empowers farmers and agronomists to make informed decisions regarding irrigation, fertilization, and crop management. This results in optimized resource use, improved yields, and enhanced sustainability.

In conclusion, the Soil Parameter Testing System bridges the gap between traditional soil testing and smart agriculture. It offers a practical, robust, and energy-independent solution for continuous soil health monitoring, supporting the transition toward data-driven, sustainable farming practices.

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Abbreviations

Abbreviation	Full Form
ADC	Analog-to-Digital Converter
AI	Artificial Intelligence
API	Application Programming Interface
BLE	Bluetooth Low Energy
CRC	Cyclic Redundancy Check
DHT	Digital Humidity and Temperature
DS18B20	Digital Sensor 18B20 (Waterproof Temperature Sensor)
ESP32	Espressif Systems 32-bit Microcontroller
FDM	Finite Difference Method
GPIO	General Purpose Input/Output
GSM	Global System for Mobile Communication
GPRS	General Packet Radio Service
I2C	Inter-Integrated Circuit
IoT	Internet of Things
LCD	Liquid Crystal Display
Li-ion	Lithium-ion
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
NISQ	Noisy Intermediate-Scale Quantum
OLED	Organic Light Emitting Diode
OTP	One-Time Programmable
PCB	Printed Circuit Board

pH	Potential of Hydrogen
PWM	Pulse Width Modulation
QAOA	Quantum Approximate Optimization Algorithm
QEC	Quantum Error Correction
RAM	Random Access Memory
RH	Relative Humidity
SDK	Software Development Kit
SIM800L	Subscriber Identity Module GSM/GPRS Module (SIM800L)
SoC	System on Chip
TDR	Time Domain Reflectometry
UART	Universal Asynchronous Receiver/Transmitter
VCC	Voltage at the Common Collector (Supply Voltage)
VWC	Volumetric Water Content
Wi-Fi	Wireless Fidelity

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CHAPTER 1: INTRODUCTION

1.1 Background and Motivation

The agricultural sector stands at the crossroads of tradition and innovation. For centuries, the health and productivity of soil have been assessed through manual observation, empirical knowledge, and periodic laboratory testing. While these methods have served humanity well, they are increasingly challenged by the demands of modern agriculture: the need for higher yields, resource conservation, environmental sustainability, and resilience to climate variability. In this context, the digital transformation of agriculture—often termed "smart agriculture" or "precision agriculture"—has emerged as a pivotal force.

At the heart of this transformation lies the integration of the Internet of Things (IoT) into farming practices. IoT enables the seamless connection of sensors, microcontrollers, communication modules, and cloud platforms, creating intelligent networks capable of real-time environmental monitoring and automated decision-making. Among the various domains of smart agriculture, soil monitoring is particularly crucial. Soil properties such as moisture, temperature, and pH directly influence plant growth, nutrient cycling, and water management. However, these parameters are dynamic, varying not only over time but also spatially across a field. Conventional soil monitoring methods, which rely on sporadic sampling and laboratory analysis, are often too slow and coarse-grained to support timely interventions.

The motivation for this thesis arises from the pressing need to bridge this gap. By leveraging IoT technologies, it is possible to design a system that continuously monitors key soil and environmental parameters, transmits data in real time, and provides actionable insights to farmers and agronomists. Such a system has the potential to optimize irrigation, fertilization, and crop selection, thereby improving yields, conserving resources, and reducing environmental impact.

1.2 Problem Statement

Despite advances in agricultural technology, many farmers still lack access to affordable, reliable, and user-friendly soil monitoring solutions. Existing commercial systems are often prohibitively expensive or require specialized technical knowledge for installation and maintenance. Furthermore, many systems are limited in scope, monitoring only a single parameter or lacking remote data access capabilities. These limitations hinder the widespread adoption of precision agriculture, particularly in resource-constrained

settings.

The core problem addressed by this thesis is the development of a cost-effective, scalable, and easy-to-use smart soil monitoring system. The system must be capable of measuring multiple soil and environmental parameters, displaying data locally, and transmitting it remotely for further analysis. It should be robust enough for field deployment, energy-efficient for long-term operation, and flexible enough to accommodate future upgrades.

1.3 Project Overview

This thesis presents the design and implementation of an IoT-based smart soil monitoring system built around the ESP32 microcontroller. The system integrates a suite of sensors—including a DHT11 for ambient temperature and humidity, a waterproof DS18B20 for soil temperature, a capacitive soil moisture sensor, and a pH sensor—to provide a comprehensive picture of soil health. Data from these sensors is displayed in real time on an OLED screen and transmitted to a cloud platform via the SIM800L GSM module, enabling remote monitoring and analysis.

The system architecture is modular, allowing for easy addition or replacement of sensors and other components. Power management is a key consideration, with the inclusion of a buck converter and battery to support autonomous field operation. The combination of hardware and software elements is designed to ensure reliability, accuracy, and user-friendliness.

1.4 Significance and Impact

The significance of this work extends beyond the technical realm. By providing farmers with timely, accurate, and actionable data, the proposed system empowers them to make informed decisions about irrigation, fertilization, and crop management. This can lead to substantial improvements in water use efficiency, fertilizer application, and overall crop productivity. On a larger scale, the adoption of such systems can contribute to food security, resource conservation, and environmental sustainability.

Moreover, the system serves as a platform for experimentation and learning. Researchers and students can use it to study the interplay between soil conditions and plant growth, test new sensors or algorithms, and explore the potential of IoT in agriculture. Policymakers and extension workers can leverage the data generated by such systems to

design targeted interventions and support evidence-based decision-making.

1.5 Challenges

Developing a smart soil monitoring system for real-world deployment involves addressing several challenges:

- **Sensor Selection and Integration:** Choosing sensors that are accurate, durable, and compatible with the ESP32 microcontroller, and integrating them into a cohesive system.
- **Data Acquisition and Processing:** Ensuring reliable data collection from multiple sensors, filtering noise, and converting raw signals into meaningful values.
- **Power Management:** Designing algorithms to minimize energy consumption and extend battery life.
- **Wireless Communication:** Implementing robust data transmission over GSM networks, handling connectivity issues, and ensuring data security.
- **User Interface:** Providing intuitive local and remote interfaces for data visualization and system control.

1.6 Sensors

Sensors are the building blocks of any environmental monitoring system. In the context of soil monitoring, the choice of sensors determines not only what parameters can be measured, but also the accuracy, reliability, and longevity of the system.

1.6.1 Overview of Sensors Used

The system described in this thesis incorporates four primary sensors, each selected for its relevance to soil health and agricultural productivity:

- **DHT11 Temperature and Humidity Sensor:**

Measures ambient temperature and humidity, providing context for soil processes such as evaporation and microbial activity.

- **Waterproof DS18B20 Digital Temperature Sensor:**

Measures soil temperature with high precision, essential for understanding seed

germination, root development, and nutrient cycling. Its waterproof design ensures durability in moist environments.

- **Capacitive Soil Moisture Sensor:**

Measures the volumetric water content of the soil using capacitive sensing, which is less prone to corrosion and drift compared to resistive sensors. Accurate soil moisture data is critical for irrigation management.

- **pH Sensor Module:**

Measures soil pH, a key factor influencing nutrient availability, microbial activity, and crop suitability. Real-time pH monitoring allows for timely interventions to correct soil acidity or alkalinity.

1.6.2 Types of Sensors and Their Principles

Temperature Sensors:

Temperature sensors can be broadly classified into contact and non-contact types. The DS18B20 is a digital contact sensor that uses a semiconductor-based sensing element to measure temperature. Its digital output ensures immunity to signal degradation over long cable runs, which is advantageous in field deployments.

Humidity Sensors:

Humidity sensors, such as the DHT11, typically use a hygroscopic material whose electrical properties change with moisture content. The DHT11 combines a humidity sensing component with a thermistor for temperature measurement, outputting digital signals for ease of interfacing.

Soil Moisture Sensors:

Soil moisture can be measured using resistive or capacitive methods. Resistive sensors measure the electrical resistance between two probes inserted into the soil, which varies with moisture content. However, they are susceptible to corrosion and require frequent calibration. Capacitive sensors, on the other hand, measure changes in the dielectric constant of the soil, offering greater stability and longevity.

pH Sensors:

pH sensors are electrochemical devices that measure the hydrogen ion concentration in a solution. The most common type is the glass electrode, which generates a voltage

proportional to the pH level. In soil monitoring, pH sensors are typically used in conjunction with signal conditioning circuits to ensure accurate and stable readings.

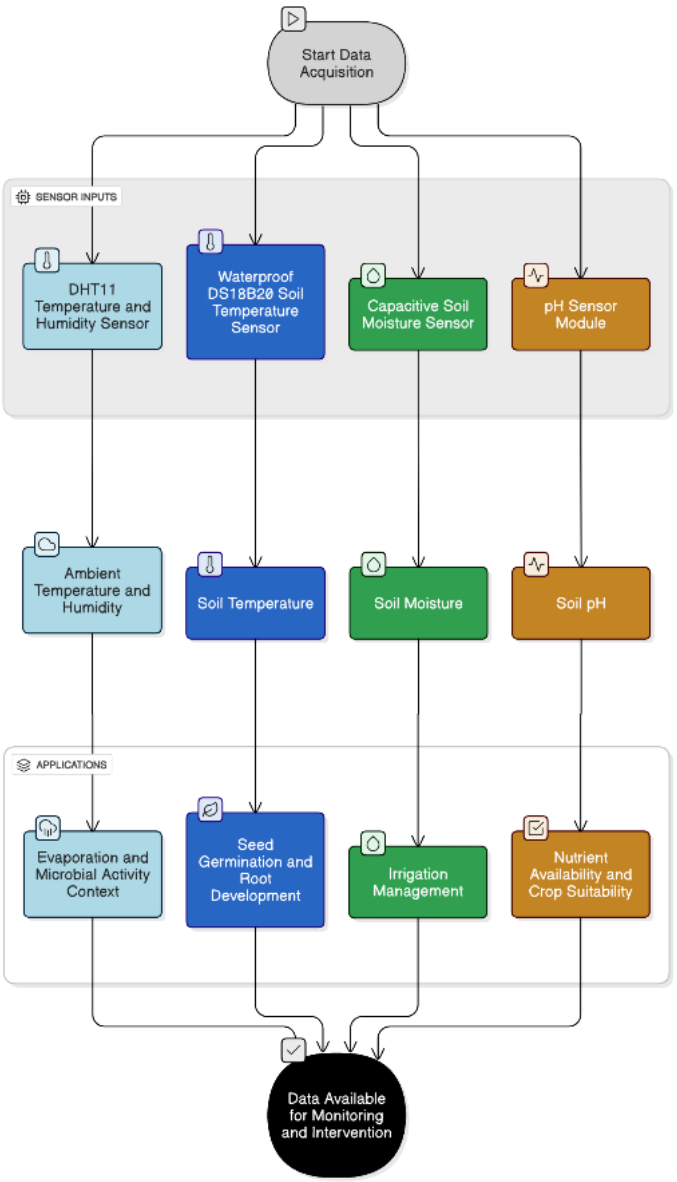


Figure 1.1 Data acquisition from Sensors.

1.7 Organization of the Thesis

To provide a clear and logical progression from foundational concepts to detailed implementation and analysis, this thesis is organized into the following chapters:

Chapter 1: Introduction

This chapter introduces the background and motivation for the project, defines the problem statement, and outlines the project overview. It discusses the significance and impact of real-time soil monitoring, highlights the main challenges, provides an

overview of the sensors used, and concludes with a summary of the thesis organization.

Chapter 2: Literature Review

This chapter reviews the scientific basis and agricultural importance of soil parameters such as moisture, temperature, humidity, and pH. It examines sensor types, the features and advantages of the ESP32 microcontroller, GSM communication, the ThingSpeak platform, OLED display technology, and the communication protocols UART and I2C.

Chapter 3: Sensor Technologies and Their Integration in Soil Monitoring

This chapter details the working principles, construction, and integration of all key sensors: the DHT11 for ambient conditions, DS18B20 for soil temperature, capacitive soil moisture sensor, and industrial-grade pH sensor. It includes a comparative discussion of digital versus analog sensors and analyzes their collective role in achieving precise, real-time soil monitoring.

Chapter 4: SIM800L GSM Module

This chapter explores the SIM800L GSM module, covering its functional overview, working principle, hardware and electrical design, software implementation, communication protocols, and its specific role within the soil monitoring system.

Chapter 5: 128×64 Monochrome OLED Display

This chapter explains the OLED display's technology, its working principle, hardware construction, electrical characteristics, I2C communication, and its integration for real-time data visualization in the monitoring system.

Chapter 6: ESP32 Microcontroller

This chapter introduces the ESP32 microcontroller, focusing on its architecture and analog-to-digital converter (ADC) features, and explains how these are leveraged for multi-sensor data acquisition.

Chapter 7: Power Management

This chapter analyzes the system's power consumption, details the battery sizing and solar panel integration, and discusses the reliability of the autonomous power system for long-term field deployment.

Chapter 8: Sensor Integration, Data Acquisition, and Results

This chapter presents the integration of all sensors and modules, provides an overview of

system wiring, describes the data acquisition and processing methodology, and discusses experimental results and their analysis.

Chapter 9: Conclusion and Future Scope

The final chapter summarizes the main findings, discusses the strengths and limitations of the system, and outlines potential directions for future research and system enhancements.

2

CHAPTER 2 : LITERATURE REVIEW

2.1 Soil Moisture

Role in Plant Growth and Soil Health

Soil moisture refers to the water content within the soil's pores. It is a fundamental variable in agriculture, acting as the primary medium through which plants absorb water and dissolved nutrients. The availability of soil moisture determines not only plant hydration but also the efficiency of nutrient uptake, since water serves as a solvent and carrier for essential minerals and organic materials. The roots of plants are highly sensitive to the soil's moisture status; both deficits and excesses can lead to stress or even plant death.

Figure 2.1 Variation of Crop concerning available moisture in the soil.[8]

Impact on Soil Processes and Microbial Activity

Beyond supporting plant hydration, soil moisture regulates soil temperature, pH, and aeration. It is essential for the metabolic activities of soil microorganisms, which decompose organic matter and recycle nutrients vital for plant growth. Microbial processes such as nitrification, denitrification, and mineralization are all moisture-dependent, with optimal activity occurring within a specific moisture range.

Soil Moisture and Environmental Interactions

Soil moisture also plays a role in local weather patterns by contributing to evaporation and plant transpiration, which in turn influence humidity and precipitation. The soil acts as a buffer, storing water from rainfall and releasing it slowly, thus preventing flooding and supporting aquifer recharge. Monitoring soil moisture

enables early warning for droughts and helps in irrigation scheduling, maximizing water use efficiency and crop yield.

Soil Texture and Water Holding Capacity

The ability of soil to retain moisture is governed by its texture and structure. Fine-textured soils like clay have higher field capacity and can store more water than sandy soils, which drain quickly and retain less moisture. Organic matter content further enhances water-holding capacity, while high soil density can impede water infiltration. Understanding these properties is crucial for determining the optimal moisture range for different crops and soil types.

2.2 Soil Temperature

Influence on Plant Physiology

Soil temperature is a key driver of plant growth and development. It affects seed germination, root expansion, and the rate of physiological processes such as photosynthesis and respiration. Each crop species has a preferred soil temperature range for optimal growth; for example, potatoes thrive at 16–21°C, while maize prefers around 25°C. Deviations from these ranges can slow growth, reduce yields, or even prevent germination.

Effects on Soil Chemistry and Microbiology

Soil temperature also controls the rate of organic matter decomposition and nutrient mineralization. Warmer soils accelerate microbial activity and enzyme reactions, increasing the availability of nutrients like nitrogen and phosphorus. Conversely, low temperatures slow these processes, potentially leading to nutrient deficiencies. The thermal properties of soil—such as heat capacity and conductivity—determine how quickly temperature changes propagate through the soil profile, impacting root zone conditions.

Interaction with Soil Moisture and Aeration

Temperature and moisture are closely linked; higher soil temperatures can increase evaporation rates, reducing available moisture. Conversely, moist soils tend to buffer temperature fluctuations, providing a more stable environment for roots and microbes. Proper management of both parameters is essential for maintaining soil structure, aeration,

and overall fertility.

2.3 Ambient Temperature and Humidity

Environmental Context for Soil Processes

Ambient temperature and humidity set the broader environmental context in which soil and plant processes occur. Air temperature influences the energy balance at the soil surface, affecting both soil temperature and the rate of moisture loss through evaporation and plant transpiration. High ambient temperatures can increase the demand for water, making soil moisture management even more critical.

Humidity's Role in Plant Water Relations

Relative humidity determines the gradient for water vapor movement from leaf surfaces to the atmosphere. In high humidity conditions, transpiration rates decrease, which can help conserve soil moisture but may also reduce nutrient uptake. Low humidity, on the other hand, increases transpiration, potentially leading to water stress if soil moisture is insufficient. The interplay between ambient temperature, humidity, and soil moisture creates a dynamic environment that requires careful monitoring to ensure optimal plant health.

Impact on Disease and Stress

Ambient humidity also affects the prevalence of plant diseases. High humidity, especially when combined with warm temperatures, creates favorable conditions for fungal and bacterial pathogens. Conversely, low humidity can cause plants to lose water rapidly, leading to wilting and reduced growth.

2.4 Soil pH

Fundamental Role in Nutrient Availability

Soil pH measures the acidity or alkalinity of the soil and is a fundamental determinant of nutrient solubility and availability. Most essential nutrients are optimally available to plants in soils with a pH between 6.0 and 7.5. Outside this range, certain nutrients become less available, while others may reach toxic concentrations. For instance, iron and manganese are more soluble in acidic soils, whereas phosphorus is most available in slightly acidic to neutral conditions.

Effects on Microbial and Enzyme Activity

Soil pH also shapes the composition and activity of soil microbial communities. Many beneficial microbes, including those involved in nitrogen fixation and organic matter decomposition, have specific pH preferences. Deviations from the optimal range can suppress microbial activity, slowing nutrient cycling and organic matter breakdown.

Crop-Specific pH Preferences and Management

Different crops have distinct pH requirements. Maintaining soil pH within the optimal range for a given crop enhances root development, nutrient uptake, and overall productivity. Managing soil pH often involves the application of amendments such as lime (to raise pH) or sulfur (to lower pH), based on regular monitoring and analysis.

Interaction with Soil Moisture

Recent studies have shown that soil moisture content can influence pH measurements, with wetter soils sometimes exhibiting higher pH values due to changes in ion mobility and solubility. This highlights the importance of considering both parameters together for accurate soil assessment and management.

Table 2.1: Influence of Soil pH on Nutrient Availability and Crop Growth[7].

Nutrient	Optimal pH Range	Availability at Low pH	Availability at High pH	Impact on Crop Growth
Nitrogen (N)	6.0 – 7.5	Reduced nitrification, lower nitrate formation	Reduced ammonium solubility	Essential for growth and chlorophyll; deficiency stunts growth and reduces yield
Phosphorus (P)	6.0 – 7.0	Forms insoluble compounds with iron and aluminum	Forms insoluble compounds with calcium	Deficiency leads to stunted growth, poor root development, and leaf yellowing
Potassium (K)	5.5 – 8.0	Leaching in acidic soils	Reduced availability due to competition with other cations	Deficiency causes poor root development, weak stems, and purple leaves

Iron (Fe)	4.0 – 6.5	More soluble, readily available	Forms insoluble hydroxides and carbonates	Deficiency (common in high pH) causes chlorosis (yellowing) and weak plant growth
Manganese (Mn)	5.0 – 6.5	More soluble, readily available	Forms insoluble compounds	Deficiency leads to interveinal chlorosis, especially in young leaves
Zinc (Zn)	5.0 – 7.0	More soluble, readily available	Forms insoluble compounds	Deficiency causes interveinal chlorosis, necrotic spots, and poor fruit set
Copper (Cu)	5.0 – 7.0	More soluble, readily available	Forms insoluble compounds	Deficiency results in stunted growth and malformed leaves
Boron (B)	5.0 – 7.0	More soluble, but potential toxicity	Reduced availability	Deficiency causes brittle stems, poor fruit set, and dieback of growing tips

2.5 Overview of Sensor Types

Sensors are integral to modern measurement, control, and automation systems, forming the interface between the physical world and digital computation. The selection of sensor types and the microcontroller platform for data acquisition, processing, and communication are pivotal in the design of any advanced monitoring system. The ESP32 microcontroller, with its rich set of features and connectivity options, has become a cornerstone for contemporary sensor-based applications, especially in the context of the Internet of Things (IoT).

Scientific Classification of Sensors

Sensors can be classified according to several scientific criteria, each reflecting a different aspect of their operation and application.

1. By Physical Principle

Sensors are often grouped by the primary physical or chemical phenomenon they exploit:

Mechanical Sensors: These detect displacement, force, pressure, or vibration, and include strain gauges, accelerometers, and load cells. Mechanical sensors are widely used

in structural health monitoring and robotics.

Thermal Sensors: Devices such as thermocouples, thermistors, and resistance temperature detectors (RTDs) measure temperature by exploiting temperature-dependent material properties. These are essential in environmental, industrial, and biomedical monitoring.

Optical Sensors: These detect light intensity, wavelength, or color, using photodiodes, phototransistors, or spectrometers. Optical sensors are fundamental in imaging, spectroscopy, and environmental sensing.

Magnetic Sensors: Hall effect sensors and magnetoresistive sensors respond to magnetic fields and are crucial in position sensing, navigation, and current measurement.

Chemical Sensors: Devices like pH electrodes, gas sensors, and biosensors detect specific chemical species or concentrations, playing a central role in environmental monitoring, healthcare, and industrial process control[8].

2. By Signal Type

Analog Sensors: Produce a continuous output signal proportional to the measured parameter. These require analog-to-digital conversion for digital processing. Examples include thermistors and analog pressure sensors.

Digital Sensors: Output discrete signals, often using protocols such as I2C, SPI, or UART. Digital sensors, such as digital temperature sensors and digital accelerometers, are less susceptible to noise and are easier to integrate with microcontrollers[8][9].

3. By Power Source

Active Sensors: Generate their own electrical signal in response to a stimulus. Thermocouples and piezoelectric sensors are classic examples.

Passive Sensors: Require external excitation and respond by altering their electrical properties, such as resistance or capacitance. RTDs and capacitive humidity sensors fall into this category.

4. By Application Domain

Sensors are also classified by their intended use, such as environmental monitoring (e.g., soil moisture, air quality), industrial automation (e.g., proximity, pressure), biomedical sensing (e.g., heart rate, glucose), and smart infrastructure (e.g., vibration, strain)1.

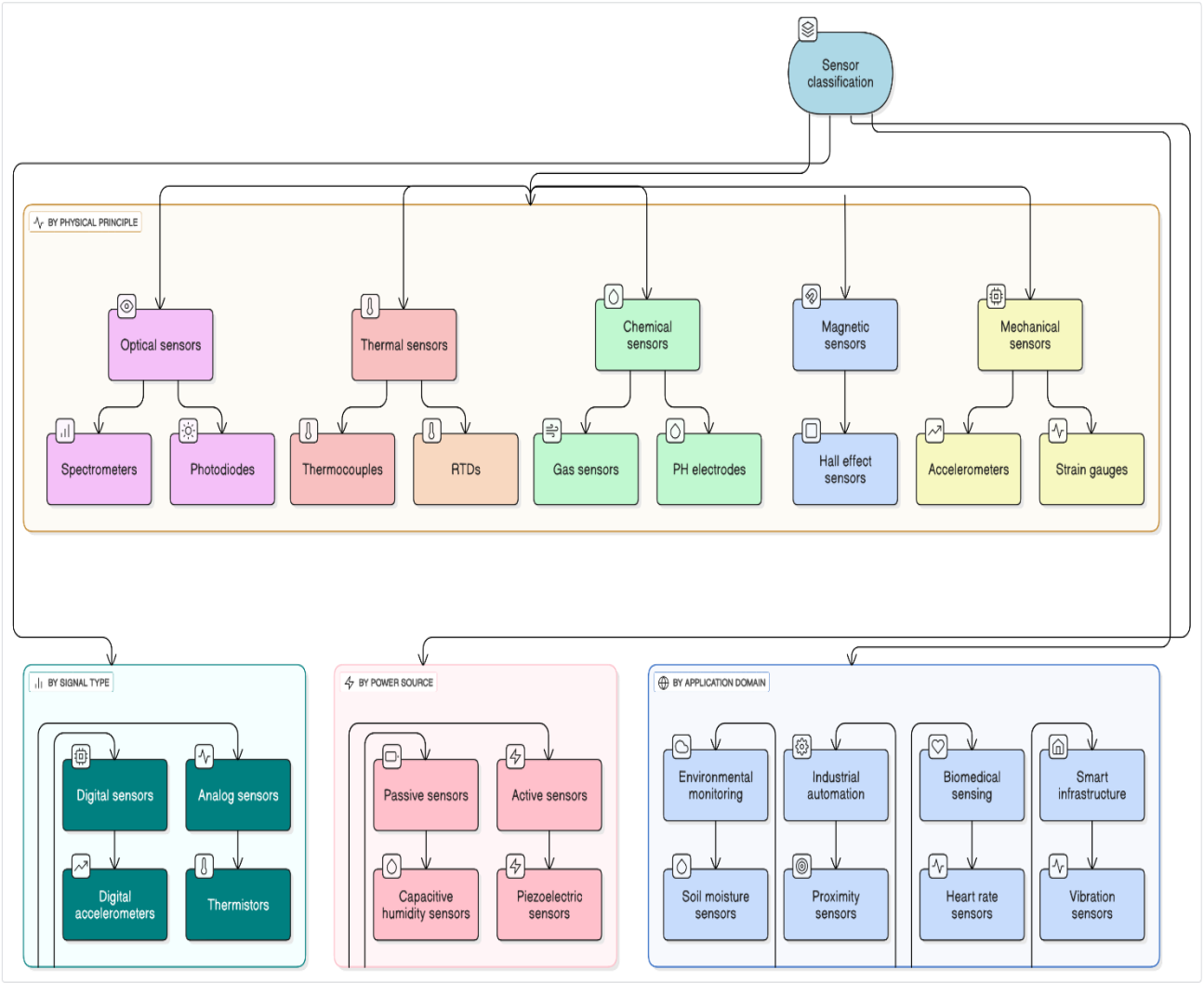


Figure 2.2 : Type of sensors

2.6 ESP32 Microcontroller: Features and Advantages

The ESP32 is a highly integrated microcontroller designed for connected applications, offering a suite of features that make it particularly suitable for sensor-rich systems.

Figure 2.3 Esp 32

1. Processing and Memory

The ESP32 incorporates a dual-core 32-bit processor (Xtensa LX6), running at up to 240 MHz, with substantial on-chip RAM (520 KB) and flash memory (typically 4 MB or more). This architecture supports multitasking, real-time data processing, and the execution of complex algorithms, even when handling multiple sensor streams simultaneously.

2. Connectivity

A defining feature of the ESP32 is its built-in Wi-Fi (802.11 b/g/n) and Bluetooth (Classic and BLE) radios, enabling wireless data transmission, device-to-device communication, and cloud integration. This connectivity is essential for IoT deployments where remote monitoring and control are required.

3. Peripheral Interfaces

The ESP32 supports a broad range of peripheral interfaces, including:

Analog-to-Digital Converters (ADC): Two 12-bit SAR ADCs with up to 18 channels, allowing simultaneous sampling of multiple analog sensors.

Digital-to-Analog Converters (DAC): For generating analog output signals.

General Purpose Input/Output (GPIO): Over 30 programmable pins for flexible device interfacing.

I2C, SPI, UART, CAN, PWM: Multiple serial and parallel communication protocols for connecting digital sensors, displays, actuators, and other modules.

4. Security and Power Management

The ESP32 integrates advanced security features, including hardware cryptographic acceleration, secure boot, and flash encryption, making it suitable for applications requiring data confidentiality and integrity. Its ultra-low power co-processor and deep sleep modes enable energy-efficient operation, a key requirement for battery-powered and remote sensor networks.

5. Scientific Applications

The versatility of the ESP32 has led to its adoption in a wide range of scientific and engineering domains, including environmental sensing, smart agriculture, wearable health devices, and industrial automation. Its ability to handle multiple sensor inputs, process data locally, and communicate wirelessly makes it a preferred platform for real-time, distributed measurement systems.

2.7 GSM (Global System for Mobile Communications)

GSM is a widely adopted standard for cellular communication, enabling mobile devices and embedded systems to transmit voice, SMS, and data over long distances. In IoT and telemetry applications, GSM modules such as SIM800L are frequently used to establish wireless connectivity in areas lacking Wi-Fi or other broadband infrastructure. These modules operate by interfacing with a microcontroller through serial communication, typically UART, and are controlled via AT commands. GSM's main advantage in IoT is its extensive coverage, allowing devices to send data from virtually any location with cellular service. The system supports both data calls and SMS-based messaging, which can be leveraged for remote monitoring, control, and alerting in applications like environmental sensing and smart agriculture. However, GSM is not suitable for real-time, safety-critical applications due to potential service interruptions and variable latency. Power consumption is another consideration, especially during data transmission bursts, which must be managed in battery-powered systems .

2.8 ThingSpeak

ThingSpeak is a cloud-based IoT analytics platform designed to aggregate, visualize, and analyze data streams from connected devices. It provides a RESTful API, allowing microcontrollers and sensors to upload data over HTTP or MQTT protocols.

Once data is received, ThingSpeak offers instant visualization through customizable graphs and enables advanced analytics using integrated MATLAB functions. This platform is particularly valuable for prototyping and proof-of-concept IoT systems, as it simplifies the process of remote data collection and analysis. ThingSpeak is widely used in environmental monitoring, energy management, and smart city projects, supporting real-time trend analysis and historical data review. Its integration with MATLAB further allows users to develop predictive algorithms and perform complex data processing directly in the cloud, making it a versatile tool for both researchers and practitioners .

2.9 OLED (Organic Light-Emitting Diode) Displays

OLED displays are advanced visual output devices that utilize organic compounds to emit light when electrically stimulated. Unlike traditional LCDs, OLEDs do not require backlighting, resulting in higher contrast ratios, deeper blacks, and wider viewing angles. They are available in a range of sizes and resolutions, with the SSD1306 being a common choice for embedded and IoT projects. OLEDs are favored in portable systems due to their low power consumption, thin profile, and ability to display crisp text and graphics even in sunlight. In IoT applications, OLED displays are typically interfaced via I2C or SPI protocols, providing real-time feedback on sensor readings, device status, or user interactions. Recent advances in OLED technology have enabled flexible and large-area displays, expanding their use in consumer electronics, automotive dashboards, and wearable devices .

2.10 UART (Universal Asynchronous Receiver-Transmitter)

UART is a fundamental hardware communication protocol used for serial data transmission between microcontrollers, sensors, and peripheral devices. It operates asynchronously, meaning data is sent without a shared clock signal. Instead, both sender and receiver agree on parameters such as baud rate, parity, and stop bits to ensure reliable communication. UART is widely used due to its simplicity, low cost, and effectiveness for low- to moderate-speed data transfer. In embedded and IoT systems, UART is the primary interface for GSM modules, GPS receivers, and other serial devices. The protocol’s full-duplex capability allows simultaneous transmission and reception of data. Modern UART designs for IoT applications incorporate power-saving features, adaptive baud rates, and error correction mechanisms to enhance reliability and efficiency, especially in energy-constrained environments .

2.11 I2C (Inter-Integrated Circuit)

I2C is a synchronous, multi-master, multi-slave serial communication protocol developed to facilitate communication between integrated circuits on the same board. It uses only two lines—SDA (Serial Data) and SCL (Serial Clock)—to transfer data, minimizing pin usage and simplifying PCB design. Each device on the I2C bus has a unique address, allowing a single master to communicate with multiple slaves efficiently. I2C is widely adopted in embedded systems for connecting sensors, memory modules, real-time clocks, and displays such as OLEDs. The protocol supports various clock speeds, including standard (100 kbit/s), fast (400 kbit/s), and high-speed (3.4 Mbit/s) modes. Its bidirectional data line allows both master and slave devices to transmit and receive data, enabling flexible and scalable system architectures. I2C's simplicity, scalability, and robustness make it a preferred choice for sensor and peripheral integration in IoT and automation applications.

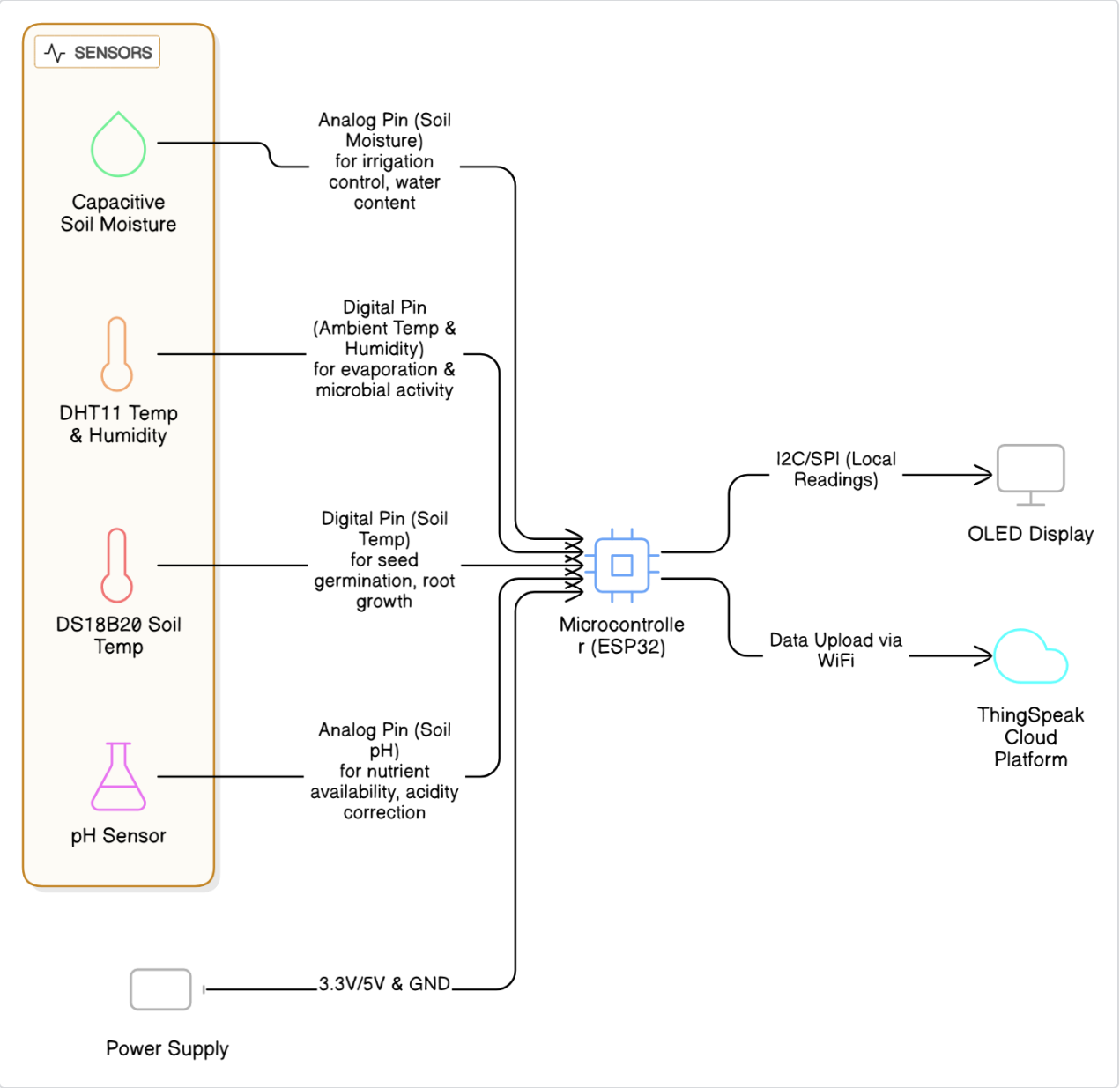

SENSORS
Capacitive Soil Moisture
DHT11 Temp & Humidity
DS18B20 Soil Temp
pH Sensor
Analog Pin (Soil Moisture) for irrigation control, water content
Digital Pin (Ambient Temp & Humidity) for evaporation & microbial activity
Digital Pin (Soil Temp) for seed germination, root growth
Analog Pin (Soil pH) for nutrient availability, acidity correction
3.3V/5V & GND
Power Supply
Microcontroller (ESP32)
I2C/SPI (Local Readings)
OLED Display
Data Upload via WiFi
ThingSpeak Cloud Platform

Figure 2.4 Complete Dataflow from sensor to display

3

Chapter 3: Sensor Technologies and Their Integration in Soil Monitoring

3.1. DHT11 – Ambient Temperature and Humidity Sensor (Digital)

Figure 3.1 DHT 11

3.1.1 Technical Analysis and Explanation

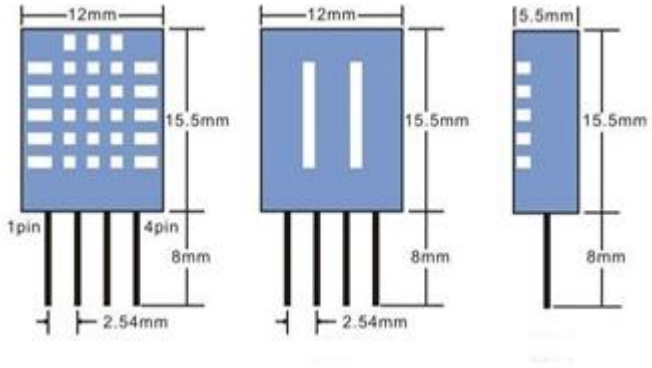


Figure 3.2 DHT 11 measurements. [1]

The DHT11 is a compact digital sensor designed to measure ambient temperature and relative humidity. In agricultural IoT systems, its primary role is to provide environmental context for soil processes, such as evaporation rates and plant transpiration. Monitoring these parameters helps optimize irrigation schedules and maintain suitable microclimates for crops. The DHT11 is favored in agricultural deployments for its low cost, factory calibration, and direct digital output, which simplifies integration with microcontrollers like the ESP32. Its single-wire communication protocol reduces wiring complexity and makes it suitable for distributed sensor networks in the field.

Compared to more advanced sensors, the DHT11 offers moderate accuracy (±2°C for temperature, ±5% for humidity), but this is generally sufficient for trend monitoring and environmental control in precision agriculture. Its low power consumption and robust digital interface make it ideal for battery-powered, remote IoT nodes.

3.1.2 Working Principle

The DHT11 combines two sensing elements: a Negative Temperature Coefficient (NTC) thermistor for temperature and a capacitive humidity sensor. The NTC thermistor's resistance decreases as temperature rises, producing a voltage that is sampled by the sensor's internal microcontroller. The humidity element consists of a hygroscopic polymer film sandwiched between electrodes; as ambient humidity changes, the dielectric constant of the film shifts, altering the capacitance. The microcontroller digitizes both signals, applies calibration coefficients, and prepares the data for output.

3.1.3 Signal Generation and Input/Output Characteristics

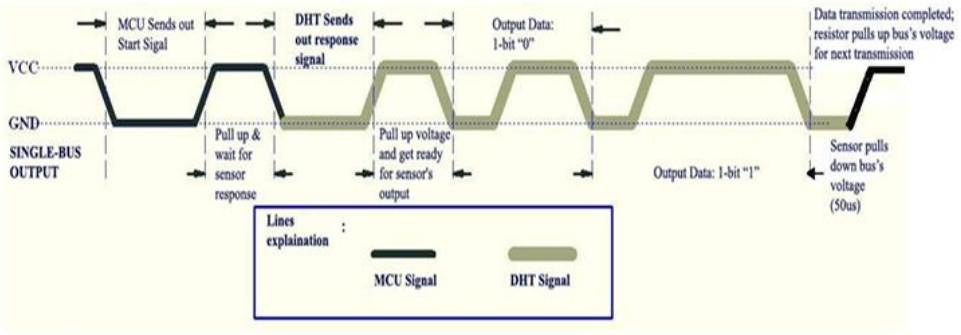

MCU Sends out Start Sigal
DHT Sends out response signal
Output Data: 1-bit "0"
Data transmission completed; resistor pulls up bus's voltage for next transmission
VCC
GND
SINGLE-BUS OUTPUT
Pull up & wait for sensor response
Pull up voltage and get ready for sensor's output
Output Data: 1-bit "1"
Sensor pulls down bus's voltage (50us)
Lines explaination :
MCU Signal
DHT Signal

Figure 3.3: DHT 11 communication with MCU [1]

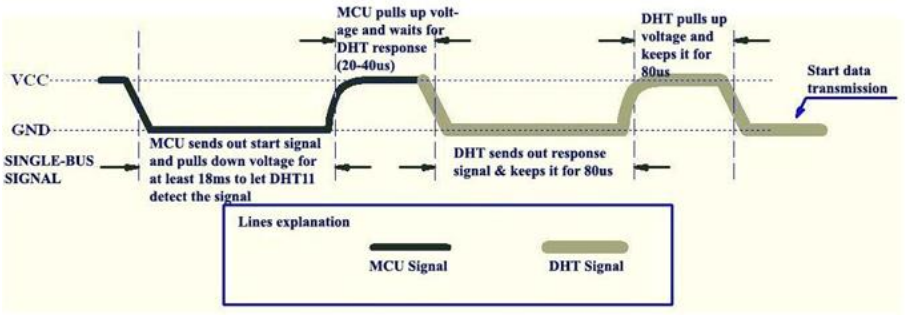

MCU pulls up voltage and waits for DHT response (20-40us)
DHT pulls up voltage and keeps it for 80us
Start data transmission
VCC
GND
SINGLE-BUS SIGNAL
MCU sends out start signal and pulls down voltage for at least 18ms to let DHT11 detect the signal
DHT sends out response signal & keeps it for 80us
Lines explanation
MCU Signal
DHT Signal

Figure 3.4: The MCU triggers the start sequence, and the DHT sensor replies accordingly [1]

The DHT11 outputs a 40-bit digital data packet containing humidity, temperature, and a checksum for error detection. Communication is initiated by the ESP32 sending a start pulse; the sensor then responds with a sequence of timed voltage pulses representing binary data. The output is a single-wire digital signal, immune to analog noise, and directly compatible with ESP32 GPIOs. The sensor operates at 3.3V or 5V, with minimal current draw, making it suitable for energy-constrained applications. The typical measurement

range is 0–50°C for temperature and 20–90% RH for humidity, with a resolution of 1°C and 1% RH.

3.2. DS18B20 – Waterproof Soil Temperature Sensor (Digital, 1-Wire)

Figure 3.5 DS18B20 sensor [2]

3.2.1 Technical Analysis and Explanation

The DS18B20 is a digital temperature sensor encased in a waterproof stainless steel probe, making it ideal for direct soil insertion and harsh agricultural environments. It is widely used for monitoring soil temperature at various depths, a key parameter influencing seed germination, root development, and microbial activity. The DS18B20's digital 1-Wire interface allows multiple sensors to be daisy-chained on a single data line, enabling scalable, distributed temperature monitoring across large fields.

This sensor is chosen over analog alternatives due to its high accuracy (±0.5°C in the critical range), resistance to signal degradation, and ease of integration. The factory-calibrated, digital output eliminates the need for user calibration and reduces susceptibility to electrical noise, a significant advantage in outdoor deployments.

3.2.2 Working Principle

Internally, the DS18B20 uses a silicon bandgap temperature sensing element. The voltage difference across two semiconductor junctions changes predictably with

temperature. This analog voltage is digitized by an on-chip ADC, with selectable resolution from 9 to 12 bits. The digital value is stored in the sensor's scratchpad memory, ready for retrieval by the microcontroller via the 1-Wire protocol.

3.2.3 Signal Generation and Input/Output Characteristics

Temperature (°C)	Digital Output (Binary)	Digital Output (Hex)
+125	0000 0111 1101 0000	07D0h
+85	0000 0101 0101 0000	0550h
+25.0625	0000 0001 1001 0001	0191h
+10.125	0000 0000 1010 0010	00A2h
+0.5	0000 0000 0000 1000	0008h
0	0000 0000 0000 0000	0000h
-0.5	1111 1111 1111 1000	FFF8h
-10.125	1111 1111 0111 1110	FF5Eh
-25.0625	1111 1110 0110 1111	FE6Fh
-55	1111 1100 1001 0000	FC90h

Table 3.1: Temperature to digital output relation [2]

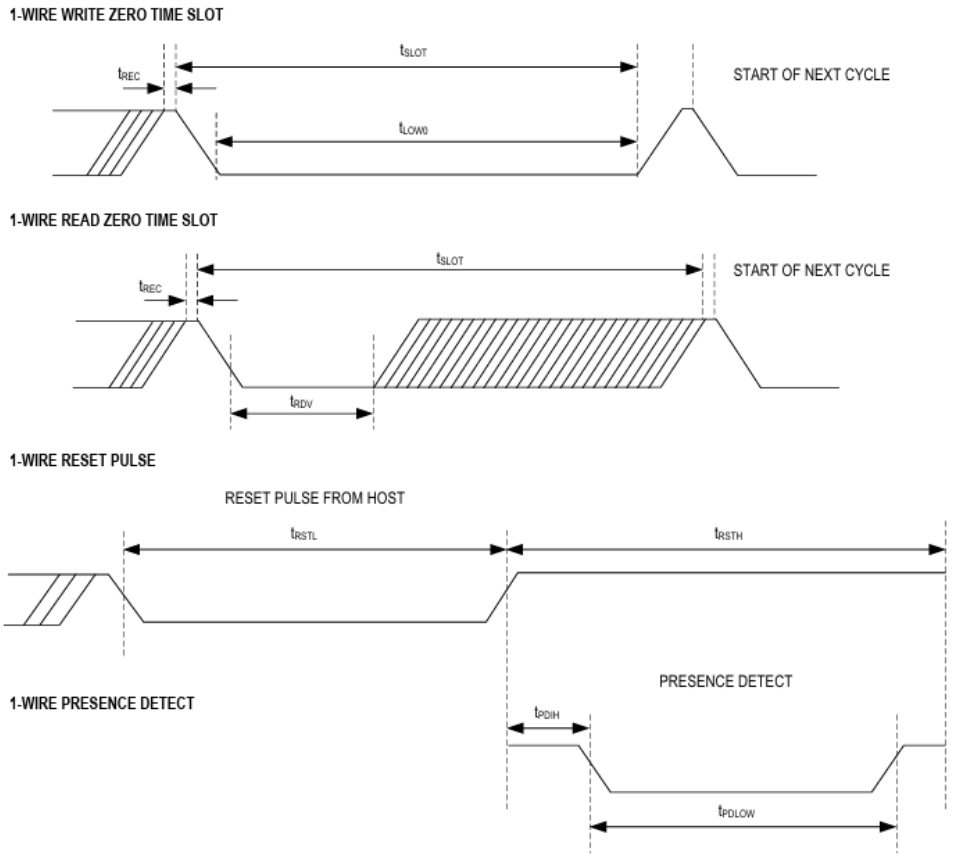


Figure 3.6 Timing diagram [2]

The DS18B20 outputs temperature data as a digital packet over a single data line, using the 1-Wire protocol. Each sensor has a unique 64-bit serial address, allowing the ESP32 to individually address and read multiple sensors on the same bus. The output resolution is configurable: 0.5°C at 9 bits, down to 0.0625°C at 12 bits. The sensor operates from 3.0V to 5.5V and draws very little current (~1mA during measurement). A pull-up resistor is required on the data line for reliable communication. The ESP32 can interface directly with the sensor's logic levels, and libraries are available for seamless integration.

3.3. Capacitive Soil Moisture Sensor (Analog)

3.3.1 Technical Analysis and Explanation

Figure 3.7: Capacitive soil moisture sensors

Capacitive soil moisture sensors are essential for measuring the volumetric water content of soil, a critical variable for irrigation management and plant health. Unlike resistive sensors, which suffer from corrosion and drift, capacitive sensors use coated electrodes to detect changes in soil dielectric constant, offering greater stability and longevity. Their analog output provides continuous, high-resolution data, making them suitable for real-time irrigation scheduling and water resource optimization in precision agriculture.

These sensors are selected over resistive types for their non-corrosive design and over advanced TDR sensors for their cost-effectiveness and ease of deployment in large-scale IoT networks.

3.3.2 Working Principle

The sensor consists of two interdigitated electrodes forming a capacitor. When inserted into soil, the dielectric constant between the electrodes changes with soil moisture content—water has a much higher dielectric constant than dry soil. This change in capacitance is incorporated into an oscillator or voltage divider circuit, converting the

capacitance variation into a measurable analog voltage or frequency. The output voltage decreases as soil moisture increases, providing a direct indication of water content.

3.3.3 Signal Generation and Input/Output Characteristics

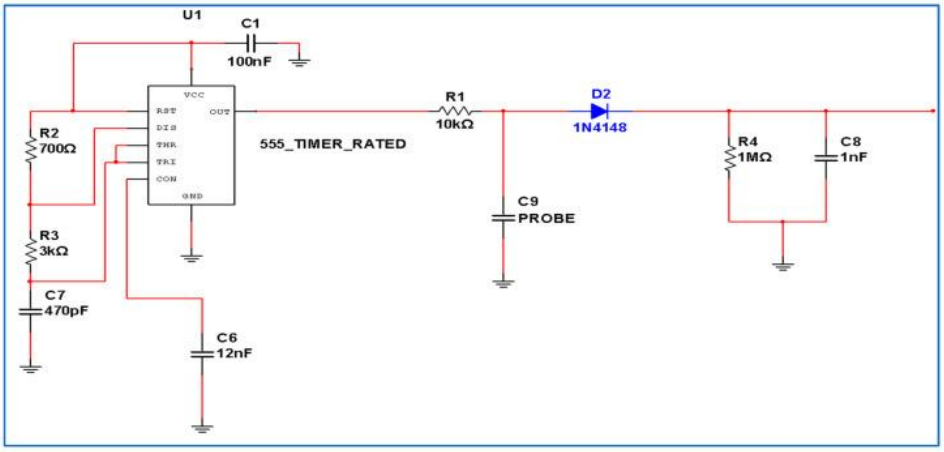


Figure 3.8: Circuit diagram [3]

The capacitive soil moisture sensor outputs a continuous analog voltage, typically in the 0–3.3V or 0–5V range, depending on the supply voltage. This voltage is inversely proportional to soil moisture: higher moisture yields lower voltage. The ESP32's 12-bit ADC digitizes this signal, allowing for fine-grained measurement and calibration to specific soil types. The sensor draws minimal current (usually <5mA), supporting battery or solar-powered operation. Calibration against gravimetric soil moisture is recommended for accurate field deployment.

3.4. Industrial-Grade pH Sensor (Analog)

Figure 3.9: Industrial-grade pH sensor

3.4.1 Technical Analysis and Explanation

Table 3.2: Industrial pH Sensor Technical Specifications [4]

Parameter	Specification
Sensor Model	Industrial-grade pH sensor
pH Range	0 to 14
Output Voltage Range	-414 mV to +414 mV
Reference Electrode	Ag/AgCl with gel electrolyte
Membrane Material	PTFE (Polytetrafluoroethylene)
Salt Bridge	Porous ceramic or PTFE junction
Operating Voltage	9 V (amplification stage)
Signal Conditioning	Op-amp or pH front-end IC required

Industrial-grade pH sensors are deployed to monitor soil acidity or alkalinity, a key factor in nutrient availability and crop suitability. Accurate, real-time pH monitoring enables targeted lime or sulfur application, optimizing fertilizer efficiency and preventing nutrient lockout. These sensors are engineered for long-term field use, featuring robust glass or solid-state electrodes, PTFE or ceramic junctions, and chemical-resistant encapsulation.

They are chosen over simple laboratory electrodes for their durability, stability, and compatibility with continuous, unattended monitoring in challenging soil environments.

3.4.2 Working Principle

The core of the pH sensor is an electrochemical cell comprising a measuring electrode (glass or solid-state membrane) and a reference electrode (typically Ag/AgCl in gel). When inserted into moist soil, the measuring electrode develops a potential proportional to the hydrogen ion concentration (pH), while the reference provides a stable baseline. The voltage difference, governed by the Nernst equation, varies linearly with pH. The signal is weak (typically -414mV to +414mV for pH 0–14) and must be amplified before digitization.

3.4.3 Signal Generation and Input/Output Characteristics

The sensor’s output is a low-level analog voltage, requiring a high-input-impedance amplifier to boost the signal to a 0–3.3V or 0–5V range suitable for the ESP32’s

ADC. The amplified signal is then digitized and processed to yield a pH value. The sensor is powered by a 9V battery or regulated supply to support the amplifier circuit. Calibration is essential, typically using standard buffer solutions, to ensure accurate conversion from voltage to pH. The analog nature of the output requires careful filtering and shielding to minimize noise.

3.5. Comparative Discussion: Digital vs. Analog Sensors

Feature	Analog Sensors (Moisture, pH)	Digital Sensors (DHT11, DS18B20)
Accuracy	High if calibrated, sensitive to drift	Factory-calibrated, stable over time
Integration	Requires ADC, signal conditioning, filtering	Direct GPIO interface, minimal circuitry
Power Use	May be higher (continuous operation, op-amp)	Low, can be duty-cycled efficiently
Noise Immunity	Prone to electrical noise, needs shielding	Robust to noise, reliable over long cables
Resolution	Continuous (limited by ADC)	Finite (set by protocol, e.g., 12 bits)
Scalability	Limited by ADC channels	Easily scalable (e.g., 1-Wire bus)
Field Suitability	Durable if protected, needs calibration	Plug-and-play, minimal maintenance

Analog sensors excel in providing continuous, high-resolution data and are often more flexible in terms of measurement range and soil adaptation. However, they require careful calibration, signal conditioning, and are more susceptible to noise, especially over long cable runs. Digital sensors, by contrast, offer robust, noise-immune data transmission, factory calibration, and simple integration, making them ideal for distributed, scalable IoT systems.

3.6. Collective Role of Sensors in Precise and Real-Time Soil Monitoring

The integration of DHT11, DS18B20, capacitive soil moisture, and industrial-grade pH sensors with the ESP32 microcontroller creates a comprehensive soil monitoring system tailored for precision agriculture. Each sensor addresses a specific parameter—ambient conditions, soil temperature, moisture, and pH providing a holistic view of the soil environment. The ESP32's multi-protocol support, high-resolution ADC, and robust processing capabilities enable seamless data acquisition, local processing, and wireless transmission.

By combining digital and analog sensors, the system balances ease of integration, measurement accuracy, and field robustness. Real-time, site-specific data empowers farmers to make informed decisions on irrigation, fertilization, and crop management, ultimately improving yields, resource efficiency, and sustainability in modern agriculture.

4

Chapter 4: SIM800L GSM Module

4.1 Overview of SIM800L Module

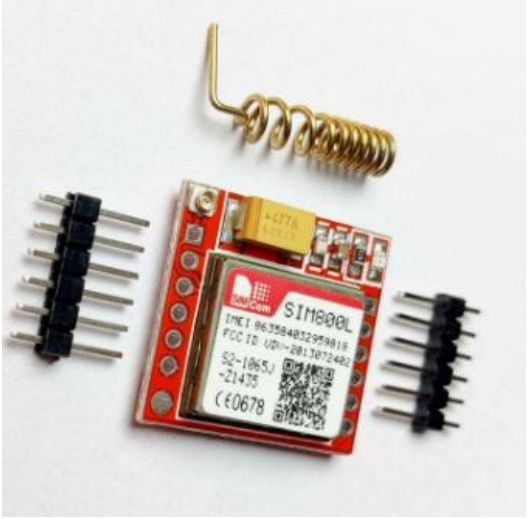


Figure 4.1 Sim800L

The SIM800L is a compact, quad-band GSM/GPRS module designed to provide wireless communication capabilities to embedded systems such as the ESP32 or NodeMCU. Supporting GSM frequencies 850/900/1800/1900 MHz, it enables global connectivity for remote sensing applications. The module is capable of voice calls, SMS, and, most critically for IoT, packet data transmission via GPRS. Its small footprint, low cost, and efficient power management make it particularly attractive for agricultural automation, remote environmental monitoring, and other scenarios where WiFi infrastructure is lacking or unreliable. Numerous IEEE and ScienceDirect studies highlight the adoption of SIM800L and similar GSM modules in field-deployed sensor networks, especially for precision agriculture and environmental data logging in rural or isolated locations.

4.2 Working Principle and Network Functionality

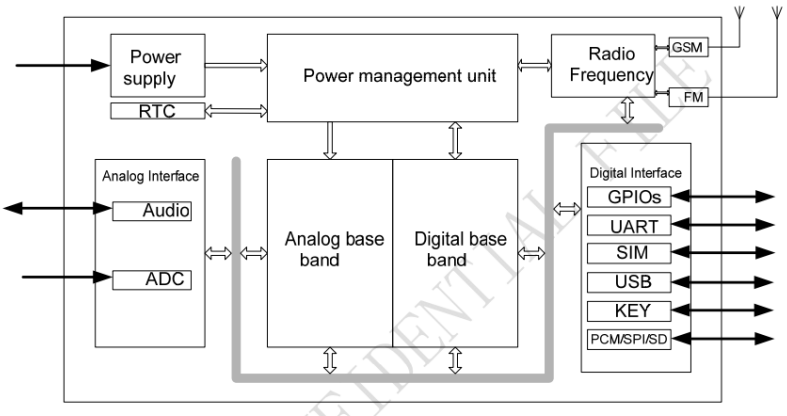


Figure 4.2 functional block diagram [5]

The SIM800L operates by interfacing with a 2G GSM cellular network. Upon power-up, the module scans for available GSM signals, authenticates with the SIM card, and registers with the local cellular network. Communication with a host microcontroller is achieved via a UART interface, using the industry-standard AT command set. These commands allow the microcontroller to control all aspects of the module's operation, from network registration and SMS transmission to establishing TCP/UDP connections for GPRS data transfer.

For IoT applications, the module is typically programmed to initiate a data session (using GPRS) and establish a TCP/IP connection to a cloud platform such as ThingSpeak or a custom server. Sensor data—such as soil moisture, temperature, or pH readings—is formatted and transmitted as HTTP POST requests or via MQTT, enabling real-time remote monitoring and analytics. The architecture can be visualized as:

This end-to-end communication enables automated, real-time data logging and alerting from field sensors to centralized dashboards or mobile devices, as demonstrated in several IEEE and ScienceDirect case studies on agricultural IoT deployments.

4.3 Hardware and Electrical Design

Power Supply and Current Requirements:

The SIM800L requires a regulated power supply between 3.7V and 4.2V, with 4V being optimal for stable operation. During data transmission bursts, the current draw can spike up to 2A, necessitating a robust power source—commonly a dedicated low-dropout (LDO) regulator or a Li-ion battery. Power supply design must incorporate decoupling capacitors (e.g., 10uF, 100nF) and protection diodes to handle transient currents and prevent voltage dips that could cause module resets.

Logic Levels and Pinout:

The module's UART interface operates at 3.3V logic levels, ensuring compatibility with ESP32 or NodeMCU microcontrollers. Key pins include TX (transmit), RX (receive), VCC (power), GND (ground), RST (reset), NET (network status), and ANT (antenna connection). Proper antenna selection—such as PCB, whip, or helical antennas—is crucial for reliable signal reception, especially in rural or shielded environments.

4.4 Software Implementation and Communication Protocols

The SIM800L is controlled exclusively via AT commands sent over the UART interface. Key software operations include:

SMS Alerts: Sending preformatted SMS messages for alarms or threshold breaches.

Internet Connectivity: Initiating GPRS sessions and establishing TCP/UDP sockets.

Data Upload: Transmitting sensor data to cloud platforms using HTTP POST or MQTT protocols.

Popular libraries such as TinyGSM, SoftwareSerial, and HTTPClient abstract the complexity of AT command sequences, managing connection states and response parsing. The typical data transmission workflow is as follows:

Acquire sensor data.

Format data string (e.g., JSON or URL-encoded).

Send AT commands to initiate GPRS and open a TCP connection.

Transmit data packet.

Await and parse response; retry on failure.

IEEE studies on GSM-enabled IoT devices underscore the importance of robust error handling, response verification, and retry logic to ensure data integrity in the face of network variability.

4.5 Role in Soil Monitoring System and Application Justification

Why SIM800L?

The SIM800L is particularly well-suited for soil and environmental monitoring in agricultural IoT systems due to several factors:

Coverage and Reliability: GSM networks offer broad coverage, including rural and remote regions where WiFi is impractical or unavailable. This enables autonomous, real-time data reporting from field-deployed sensors.

Cost and Integration: The module is inexpensive, readily available, and easily integrated with popular microcontrollers using standard UART interfaces.

Power Efficiency: Sleep modes and efficient power management make it viable for battery- or solar-powered deployments.

Scalability: The ability to connect multiple distributed nodes via cellular networks supports large-scale, mobile, or geographically dispersed sensor networks.

Comparison with Alternatives:

While WiFi modules offer higher data rates, they are limited by range and infrastructure requirements. LoRa and NB-IoT provide long-range, low-power communication, but require dedicated gateways and may not be feasible in all locations. IEEE and ScienceDirect case studies confirm that GSM modules like SIM800L strike an optimal balance between cost, coverage, and ease of deployment for precision agriculture and environmental monitoring.

Table 4.1: SIM800L vs. Other Communication Modules

Feature	SIM800L (GSM)	WiFi (ESP8266/ESP32)	LoRa (SX1278)	NB-IoT (SIM7020)
Range	Global (cellular)	100m (open)	2–15 km	5–15 km
Data Rate	Up to 85.6 kbps	Up to 72 Mbps	<50 kbps	<100 kbps
Power	Moderate (peaks)	Moderate	Very low	Low
Infrastructure	Cellular network	WiFi AP required	Gateway req.	NB-IoT network
Cost (node)	Low	Low	Moderate	Moderate
Mobility	High	Low	High	High

Table 4.2: SIM800L Electrical Specifications

Parameter	Value
Operating Voltage	3.7–4.2 V (typ. 4V)
Peak Current	Up to 2A (transmit burst)
Logic Level	3.3V UART
Frequency Bands	850/900/1800/1900 MHz
Data Rate	85.6 kbps (DL), 42.8 kbps (UL)

5

Chapter 5: 128×64 Monochrome OLED Display

5.1 Overview of the OLED 128×64 Display Module

Figure 5.1 OLED display module

Organic Light-Emitting Diode (OLED) technology represents a significant advancement in display engineering, particularly for embedded and IoT systems. Unlike traditional LCDs, OLED displays are self-emissive: each pixel generates its own light through organic semiconductor layers, eliminating the need for a backlight. This results in high contrast, deep blacks, and wide viewing angles, making OLEDs especially suitable for environments with variable lighting conditions.

The 128×64 OLED module features a dot matrix of 128 horizontal by 64 vertical pixels, arranged in a monochrome (single-color) configuration. Each pixel can be individually controlled, typically displaying white or blue on a black background. This resolution strikes a balance between compact size and sufficient detail for textual and graphical information.

The module is usually driven by an SSD1306 controller IC, which manages pixel addressing, display memory, and refresh cycles. The SSD1306 supports I2C communication—a two-wire serial protocol (data and clock)—which greatly simplifies wiring and integration with microcontrollers such as the ESP32 or NodeMCU. This minimal wiring is a key reason for the widespread adoption of such modules in portable, low-power, and space-constrained IoT devices.

5.2 Working Principle of OLED Technology

OLED displays function by injecting current through organic semiconductor layers sandwiched between a transparent anode (commonly indium tin oxide, ITO) and a metallic cathode. When a voltage is applied, electrons and holes recombine in the emissive layer, resulting in photon emission—this is the light seen by the user.

Each pixel in the 128×64 matrix is individually addressed and controlled by the SSD1306 driver. The controller manages a display buffer (GRAM), where each bit corresponds to a pixel's on/off state. Through digital addressing, the microcontroller can manipulate pixels to render text, icons, or simple graphics.

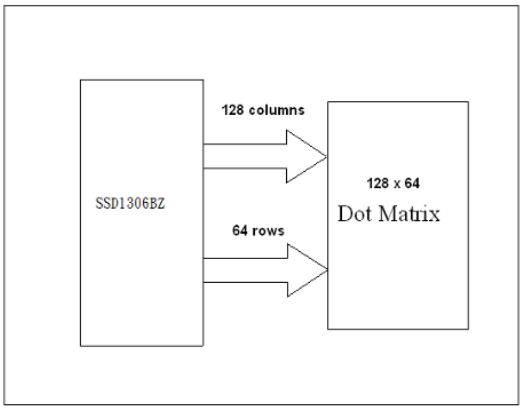


Figure 5.1: Functional Block Diagram[6]

The organic layers are typically deposited using vacuum thermal evaporation or inkjet printing, and the emissive material often includes compounds like tris(8-hydroxyquinolinato)aluminum (Alq3). The SSD1306 controller receives display data via I2C, decodes the buffer, and switches pixels on or off accordingly. This architecture allows for fast refresh rates and precise control, essential for real-time sensor data display in field applications.

5.3 Hardware Construction and Electrical Characteristics

The OLED display's substrate is typically glass or flexible polyimide, providing mechanical support and transparency. The anode layer, made from ITO, is both conductive and optically transparent, allowing emitted light to pass through. The organic layers are sandwiched between the anode and an aluminum cathode, forming the active light-emitting region.

Key Electrical Characteristics:

- **Supply Voltage:** 3.3V–5V, compatible with most microcontrollers.
- **Interface:** I2C (SDA, SCL, VCC, GND).
- **Power Consumption:** Low; only lit pixels draw current, making the display highly energy-efficient—ideal for battery-powered soil monitoring systems.

Pinout:

- **VCC:** Power supply (3.3V or 5V)
- **GND:** Ground
- **SDA:** Serial Data (I2C)
- **SCL:** Serial Clock (I2C)

Table 5.1 Connection Table (ESP32 Example):

OLED Pin	ESP32 Pin (Example)
VCC	3.3V
GND	GND
SDA	GPIO21
SCL	GPIO22

The compact and robust construction of OLED modules—often less than 2mm thick—allows them to be integrated into sealed, weather-resistant enclosures for field-deployable IoT devices.

5.4 Display Communication via I2C Protocol

The I2C protocol is a synchronous, two-wire serial interface that enables multiple devices to share a common bus. Each device is identified by a unique 7-bit address, with OLED modules commonly using 0x3C or 0x78. Communication involves sequences of command and data bytes, with the SSD1306 controller distinguishing between them via a control byte.

Commands: Set display parameters (contrast, addressing mode, power on/off).

Data: Update the pixel buffer (GRAM) for rendering text and graphics.

Data Transmission Structure:

Start condition (initiated by the microcontroller).

Send device address (e.g., 0x3C).

Send control byte (indicates command or data).

Send command/data bytes.

Stop condition.

I2C bus speeds are typically 100 kHz (standard) or 400 kHz (fast), balancing throughput and power efficiency.

Libraries such as U8g2 and Adafruit SSD1306 abstract the low-level protocol, providing high-level APIs for drawing text, shapes, and icons. These libraries manage a display buffer in RAM, converting user commands into pixel data sent via I2C for real-time updates.

5.5 Integration in Soil Monitoring System

The OLED 128×64 display is particularly advantageous for IoT-based soil monitoring due to its:

- **High Contrast and Readability**: OLEDs offer excellent visibility in both direct sunlight and low-light conditions, outperforming most LCDs in outdoor environments.

- **Compact Size**: The thin, lightweight module fits easily into small, rugged enclosures, preserving device portability and weather resistance.

- **Low Power Consumption**: Only active pixels consume power, making OLEDs ideal for battery- or solar-powered ESP32-based systems deployed in remote fields.

- **Real-Time Data Display:** The display can show multiple sensor readings (soil moisture, pH, temperature, humidity) simultaneously, along with status icons, battery level, and network signal strength.

- **Immediate Feedback:** On-site users can quickly assess soil and environmental conditions without external devices, enhancing usability and reliability in the field.

Comparison with Other Displays:

LCDs: Require backlighting, have limited viewing angles, and higher power consumption.

TFTs: Offer color and higher resolution but are bulkier and consume more power.

E-Ink: Excellent for sunlight readability and ultra-low power, but slow refresh rates and limited color make them less suitable for dynamic, real-time data.

Table 5.2: Comparison of Display Technologies for IoT Applications

Feature	OLED 128×64	LCD (Char/Graphic)	TFT LCD	E-Ink Display
Power Consumption	Low (only lit pixels)	Moderate (backlight)	High (backlight)	Very Low
Readability	Excellent (high contrast, wide angle)	Good (limited angle)	Excellent (color)	Excellent (sunlight readable)
Resolution	128×64 pixels	Varies (e.g., 16×2 chars)	High (e.g., 320×240)	Moderate
Color Support	Monochrome	Mono/Color	Full Color	Limited (gray)
Wiring Complexity	Low (I2C: 2 wires)	Moderate	Moderate (SPI)	Low (SPI/I2C)
Size/Thickness	Thin, compact	Bulkier	Bulkier	Thin
Response Time	Fast	Moderate	Fast	Slow

6

Chapter 6: ESP32 Microcontroller

6.1 Introduction to ESP32 Architecture

The ESP32 microcontroller is a highly integrated, dual-core system-on-chip (SoC) that stands at the forefront of modern IoT and embedded system design. Its architecture is built to support real-time, multi-sensor data acquisition, processing, and wireless communication, making it an ideal platform for advanced soil monitoring systems. In the context of multi-parameter soil monitoring, the ESP32's internal resources—ranging from its analog-to-digital converters (ADCs) and versatile digital I/O to its robust communication peripherals—enable seamless interfacing with a diverse array of environmental sensors and modules.

At the heart of the ESP32 are two Tensilica LX6 cores, each capable of running tasks independently or in parallel. This dual-core arrangement allows the system to dedicate one core to time-critical sensor acquisition and processing, while the other manages communication and user interface tasks. The SoC includes 520 KB of SRAM, multiple hardware timers, and a suite of digital and analog peripherals, all interconnected via a high-speed internal bus. Integrated Wi-Fi and Bluetooth radios further extend its communication capabilities, although in many agricultural deployments, GSM modules like the SIM800L are preferred for their broader coverage in rural areas.

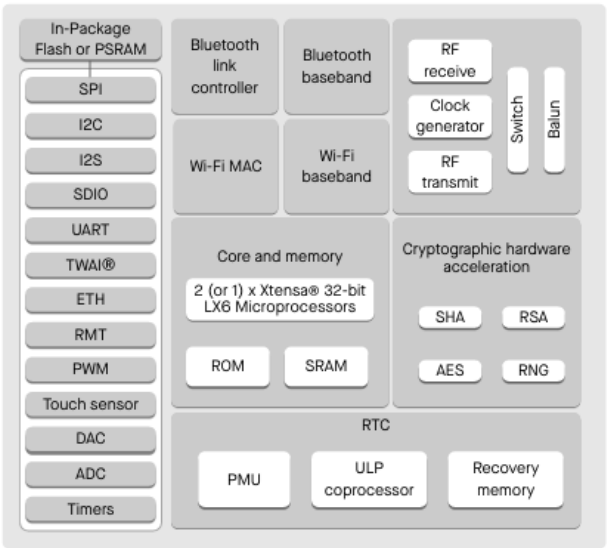


Figure 6.1 Block Diagram: ESP32 SoC Architecture [16]

This architecture enables the ESP32 to act as the central controller in a soil monitoring network, orchestrating sensor reads, data processing, display management, and wireless/cloud communication—all within a compact, energy-efficient package.

GPIO and Digital Communication Interfaces

The ESP32's general-purpose input/output (GPIO) pins are the foundation of its sensor and peripheral interfacing. Each GPIO is multiplexed, allowing it to serve multiple functions depending on the application's needs. In a soil monitoring system, digital GPIOs are used to interface with:

- **DHT11 (Temperature & Humidity Sensor):** Connected via a single-wire digital protocol, typically mapped to GPIO4. The ESP32's internal pull-up resistors and precise timing control ensure reliable data acquisition.

- **DS18B20 (Waterproof Digital Temperature Sensor):** Utilizes the OneWire protocol, interfaced through GPIO5. The ESP32's flexible pin mapping and interrupt handling support the precise timing required for OneWire communication.

- **OLED Display (SSD1306):** Communicated via I2C, with SDA and SCL lines mapped to GPIO21 and GPIO22, respectively. The ESP32's I2C driver supports clock stretching and multi-device arbitration, allowing multiple I2C peripherals to coexist on the same bus.

Table 6.1: Sensor/Device GPIO Allocation

Device/Sensor	GPIO Pin(s)	Communication Protocol
DHT11	GPIO4	Single-Wire Digital
DS18B20	GPIO5	OneWire
OLED (SSD1306)	GPIO21/22	I2C

The I2C bus's ability to address multiple devices with unique addresses (e.g., OLED at 0x3C) allows for future expansion, such as adding real-time clocks or additional displays, without increasing wiring complexity.

6.2 Analog-to-Digital Converter (ADC) in ESP32

6.2.1 Architecture of ESP32 ADC

The ESP32 is equipped with two successive approximation register (SAR) ADCs—ADC1 and ADC2—each offering up to 12-bit resolution (4096 discrete levels).

ADC1 is preferred in this project because ADC2's channels are shared with the Wi-Fi subsystem, which can cause conflicts during simultaneous operation. Each ADC supports multiple input channels, selectable via internal multiplexers.

- **Resolution:** 12 bits (0–4095)
- **Input Range:** 0–3.3V (configurable via attenuation settings)
- **Channels:** ADC1 (8 channels), ADC2 (10 channels)

6.2.2 Multiplexing in ADC Channels

The ESP32's internal multiplexer allows sequential sampling of multiple analog inputs. In the soil monitoring system:

- **Soil Moisture Sensor:** Connected to GPIO34 (ADC1_CH6)
- **pH Sensor:** Connected to GPIO35 (ADC1_CH7)

Table 6.2: ADC Channel Mapping

Sensor	GPIO Pin	ADC Unit	Channel	Voltage Range	Interpretation
Soil Moisture	GPIO34	ADC1	CH6	0–3.3V	Moisture (%)
pH Sensor	GPIO35	ADC1	CH7	0–3.3V	pH (calibrated)

Sequential ADC sampling is implemented in firmware, with each channel sampled in turn and readings filtered using moving average or median algorithms to suppress noise and outliers.

Timer and Interrupt Handling

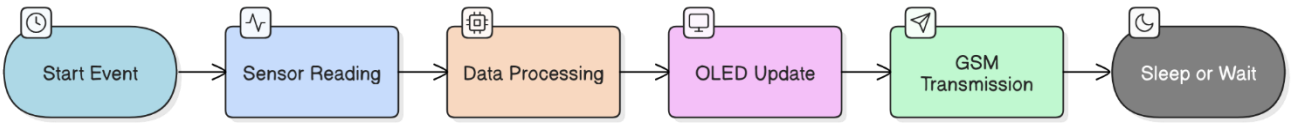
Efficient multi-sensor monitoring requires precise timing and event-driven processing. The ESP32 leverages hardware timers and FreeRTOS-based software timers to schedule periodic tasks:

- **Sensor Sampling:** Timers trigger ADC reads and digital sensor queries at fixed intervals (e.g., every 30 seconds).
- **OLED Display Updates:** A separate timer refreshes the display every few seconds, ensuring real-time feedback.

- **GSM Data Transmission:** Another timer triggers batch uploads to the cloud or GSM module, balancing data freshness with power savings.

Interrupts are used to handle asynchronous events, such as OneWire data signals or UART receive events from the SIM800L module. This non-blocking, event-driven approach prevents data loss and ensures timely system response.

Figure 6.2 : Flowchart: Data Acquisition and Processing Loop



This architecture supports both real-time monitoring and power-efficient operation, critical for autonomous field deployments.

UART Communication for SIM800L

The ESP32's UART peripherals are essential for interfacing with serial devices like the SIM800L GSM module. In this system:

- **UART2** is configured for communication with the SIM800L, using GPIO16 (TX) and GPIO17 (RX).

- **Baud Rate:** Typically set at 9600 or 115200 bps, depending on module configuration.

- **Protocol:** AT commands are sent to the SIM800L to initialize GPRS, establish TCP/IP connections, and transmit sensor data via HTTP or MQTT.

The ESP32's UART driver supports full-duplex communication, buffering, and interrupt-driven data handling. This allows the microcontroller to manage asynchronous data exchanges, parse responses, and implement robust error handling and retry logic.

This setup enables reliable, long-range wireless data transmission from remote soil monitoring stations to cloud platforms or centralized servers.

Power Management Features

While the ESP32 supports multiple low-power modes (light sleep, deep sleep),

continuous real-time monitoring often requires the device to remain active. Nevertheless, careful power management is crucial:

- **Regulated 3.3V Supply:** Ensures stable operation of the ESP32 and analog sensors.
- **Decoupling Capacitors:** Placed near ADC pins and power rails to filter noise and stabilize readings.
- **Sleep Modes:** Can be enabled during periods of inactivity to extend battery life in less time-critical deployments.

Power supply design must also account for the high current demands of GSM transmission bursts, typically handled by a dedicated LDO regulator or Li-ion battery.

Integration Summary

Table 6.3: ESP32 Subsystem Roles

Subsystem	Device/Sensor	Role	Interface
ADC1	Soil Moisture/pH	Analog Read	GPIO34/35
I2C	OLED Display	Visual Output	GPIO21/22
GPIO	DHT11, DS18B20	Digital Read	GPIO4/5
UART	SIM800L	GSM Communication	GPIO16/17
Timer	System Loop	Task Scheduling	Internal

This modular allocation of resources allows the ESP32 to manage multiple sensors, display outputs, and communication tasks efficiently, supporting scalable and robust soil monitoring networks.

7

Chapter 7: Power Management

7.1 System Power Consumption Analysis

Sensor and Module Duty Cycle

Each component is operated only as needed to maximize energy efficiency:

- **ESP32 Microcontroller:** Wakes periodically for sensor readings and communication, otherwise remains in deep sleep.
- **DHT11, DS18B20, Soil Moisture Sensor:** Each sampled once every 30 minutes.
- **pH Sensor:** Activated only once per day.
- **OLED Display:** Runs for a total of 30 minutes per day.
- **SIM800L GSM Module:** Used briefly for data uploads.

7.2 Average Power and Daily Energy Consumption

Based on the duty cycle and current draw of each component, the average current consumption is approximately 9.7 mA at a system voltage of 3.7V (Li-ion battery).

Average Power Consumption:

$$9.7\text{mA} \times 3.7\text{V} = 0.0359\,\text{W}$$

Daily Energy Consumption:

$$0.0359\text{W} \times 24,\ \text{h} = 0.86\text{Wh/day}$$

7.3 Battery Sizing and Autonomy

7.3.1. Battery Capacity and Runtime

- Battery Used: 2000 mAh (3.7V Li-ion)
- Total Energy Storage:

$$2Ah \times 3.7\,V = 7.4\,Wh$$

- Autonomy (without solar):

$$\frac{2000\,\text{mAh}}{9.7\,\text{mA}} \approx 206\,\text{hours}$$

- (over 8.5 days of continuous operation)

- This means that even without solar input, your system can run for more than a week on a full charge, providing excellent resilience during extended cloudy periods.

7.4 Solar Panel Sizing and Energy Harvesting

7.4.1 Solar Panel Output

- **Panel Used**: 3W, 5V

- **Current Output:**

$$\frac{3W}{5V} = 0.6A$$

- **Assumed Peak Sunlight Hours:** 5 hours/day

- **Daily Energy Provided:**

$$3W \times 5\,h = 15\,Wh/day$$

7.4.2. Energy Surplus

- **Daily Surplus:**

$$15\ Wh/day - 0.86\,Wh/day = 14.14\,Wh/day$$

- The solar panel provides far more energy than the system consumes each day, ensuring rapid battery recharging and robust operation even in less-than-ideal sunlight conditions.

7.5 System Integration and Reliability

Table 7.1 Summary Table

Parameter	Value/Specification
Average Current Draw	9.7 mA
Daily Energy Consumption	0.86 Wh
Battery Capacity	2000 mAh (3.7V)
Battery Autonomy	~8.5 days
Solar Panel Power	3W (5V)
Solar Daily Energy	15 Wh (5h sunlight)
Daily Energy Surplus	14.14 Wh

8

Chapter 8: Sensor Integration, Data Acquisition, and Results

8.1 Sensor and Module Integration

8.1.1 Pin Mapping and Hardware Connections

Table 8.1 : Sensor and Module Pin Mapping on ESP32

Component	Pin on ESP32	Type	Notes
DHT11 Sensor	GPIO 4	Digital Input	For ambient temperature & humidity
DS18B20 Soil Temp Sensor	GPIO 14	Digital Input	1-Wire protocol; add 4.7kΩ pull-up resistor to 3.3V
Soil Moisture Sensor	GPIO 34 (ADC1)	Analog Input	Capacitive type, less prone to corrosion
pH Sensor Module	GPIO 35 (ADC1)	Analog Input	Requires 5V power
OLED Display (SSD1306 I2C)	GPIO 21 (SDA)	I2C (SDA)	NanoOLED display
	GPIO 22 (SCL)	I2C (SCL)	
SIM800L GSM Module	GPIO 26 (RX)	UART RX	Connects to SIM800L TX
	GPIO 27 (TX)	UART TX	Connects to SIM800L RX

8.2. System Wiring Overview

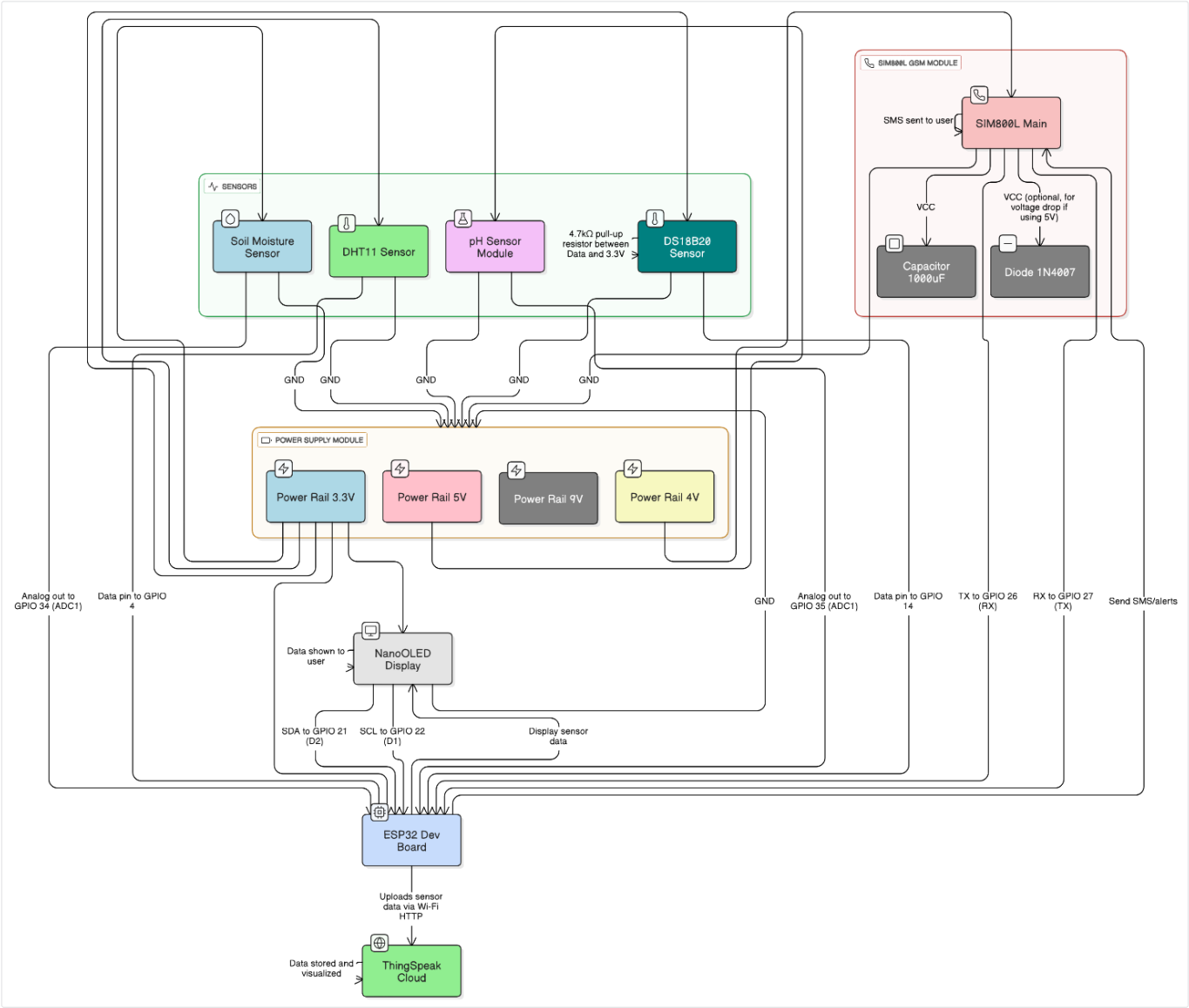


Figure 8.1 System overview

All sensors and modules are connected to the ESP32 using a combination of digital, analog, I2C, and UART interfaces. Careful attention is paid to grounding, power supply stability, and signal integrity to ensure accurate sensor readings and reliable communication.

8.3 Data Acquisition and Processing

8.3.1 Sampling Strategy

Each sensor is sampled according to its optimal duty cycle:

- DHT11, DS18B20, and Soil Moisture Sensor: Every 30 minutes.

- pH Sensor: Once per day.
- OLED Display: Activated for 30 minutes daily for user interaction.
- SIM800L GSM Module: Used for brief, periodic data uploads.

8.3.2 Data Flow

The ESP32 orchestrates sensor activation, data collection, and local processing. Acquired data is displayed on the OLED and transmitted to the cloud via the SIM800L GSM module. This ensures both immediate feedback and remote accessibility.

8.4. Experimental Results

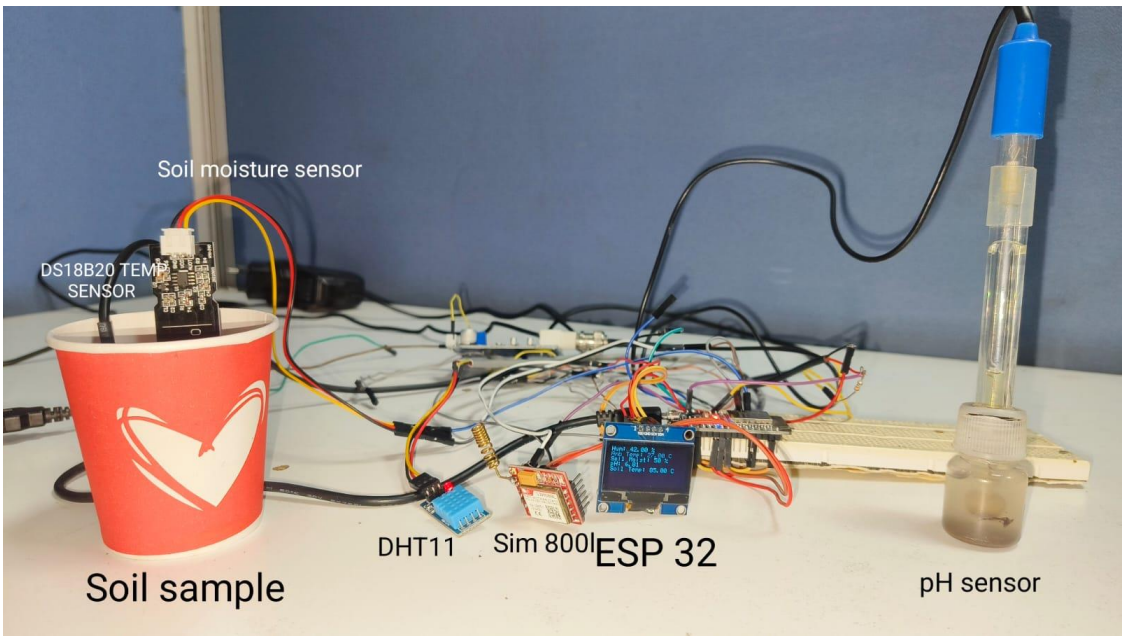


Figure 8.2 Working prototype

8.4.1 Local Sensor Output: Before and After Irrigation

Before Irrigation:

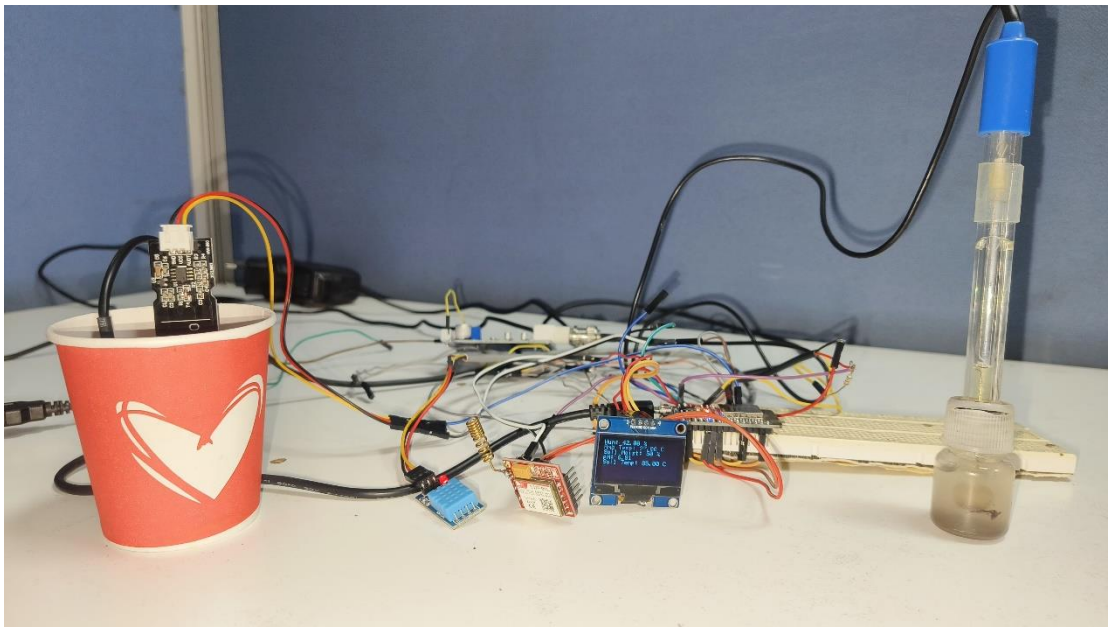


Figure 8.2 reading 1

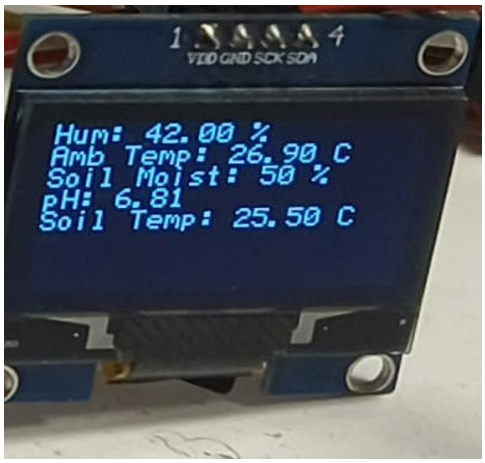


Figure 8.3 Display Output reading 1

1. Humidity	42%
2. Ambient temperature	26.9 °C
3. Soil Moisture levels	50%
4. pH levels	6.81
5. Soil Temperature	25.5 °C

Table 8.2: reading 1

This image shows the system's display and sensor readings prior to adding water to the soil sample. It establishes the baseline for soil moisture and other parameters.

- **After Irrigation**

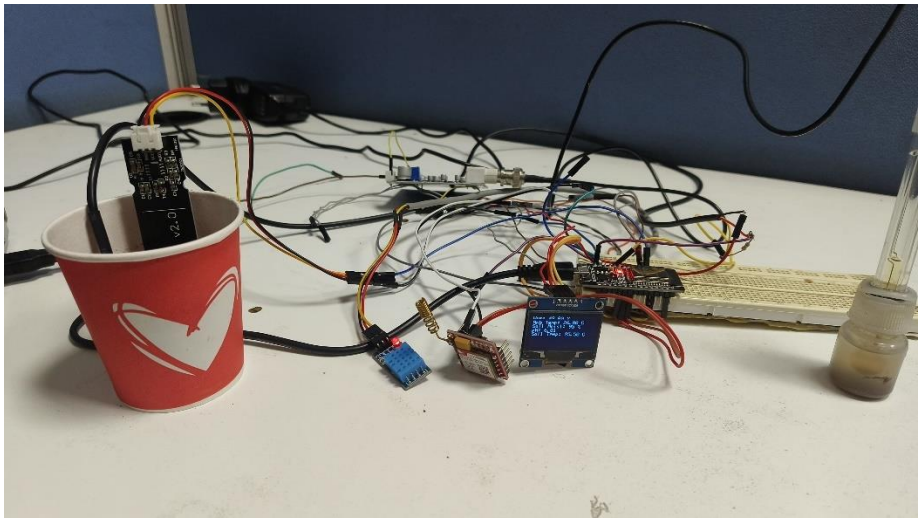


Figure 8.4: reading 2

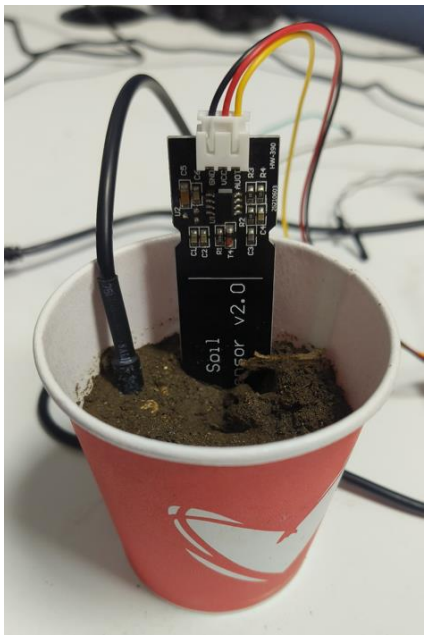


Figure 8.6: Soil sample

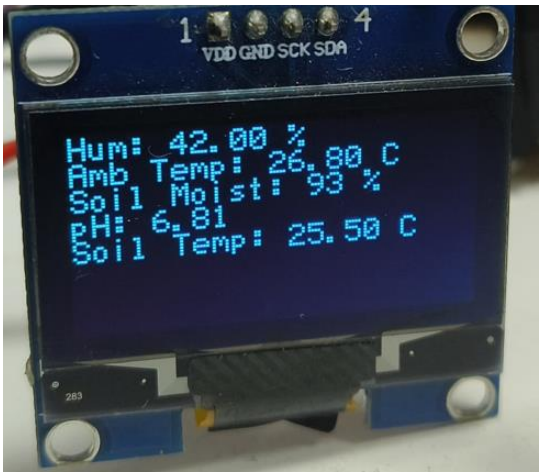


Figure 8.5: display output reading 2

1. Humidity	42%
2. Ambient temperature	26.8 °C
3. Soil Moisture levels	93%
4. pH levels	6.81
5. Soil Temperature	25.5 °C

Table 8.3: reading 2

This image captures the immediate response of the system following water application, demonstrating the sensitivity and accuracy of the soil moisture sensor and the system's ability to detect real-time changes.

11.4.2. Cloud-Based Monitoring: ThingSpeak Outputs

- **Multi-Parameter Dashboard**

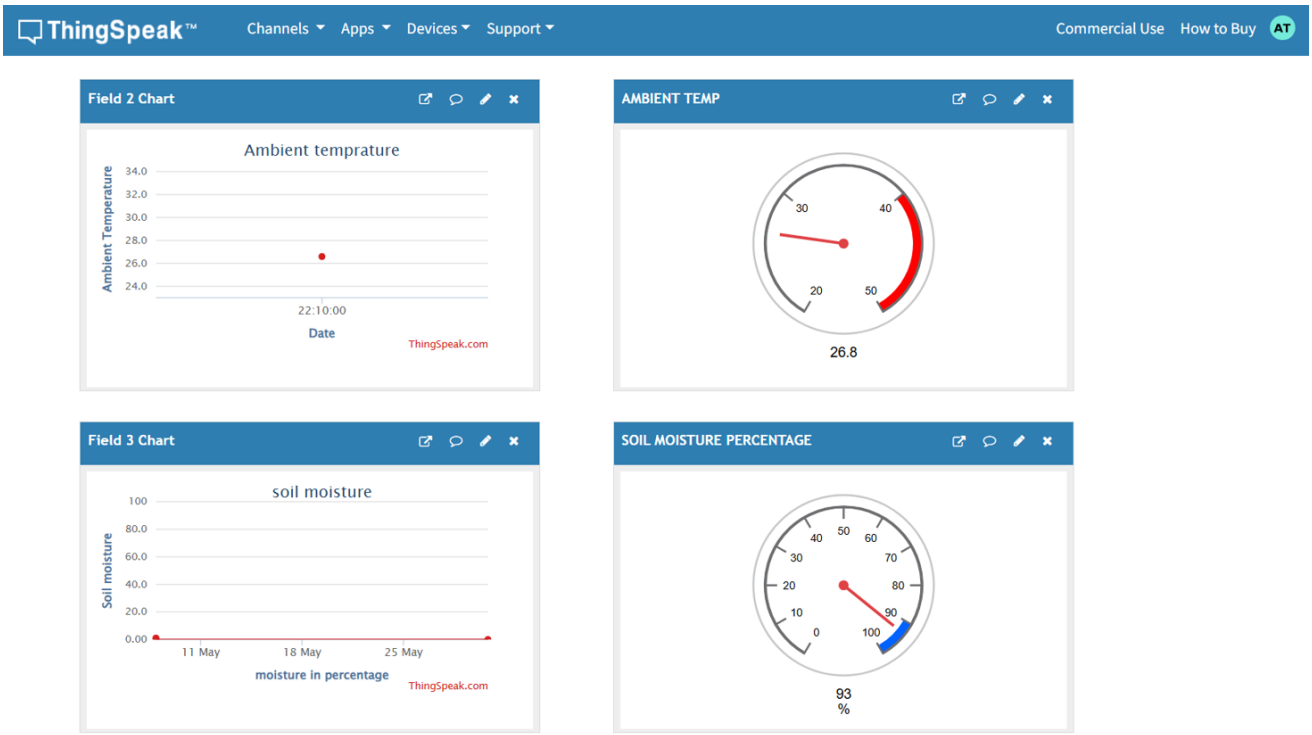


Figure 8.7: Thinkspeak Output screenshot 1

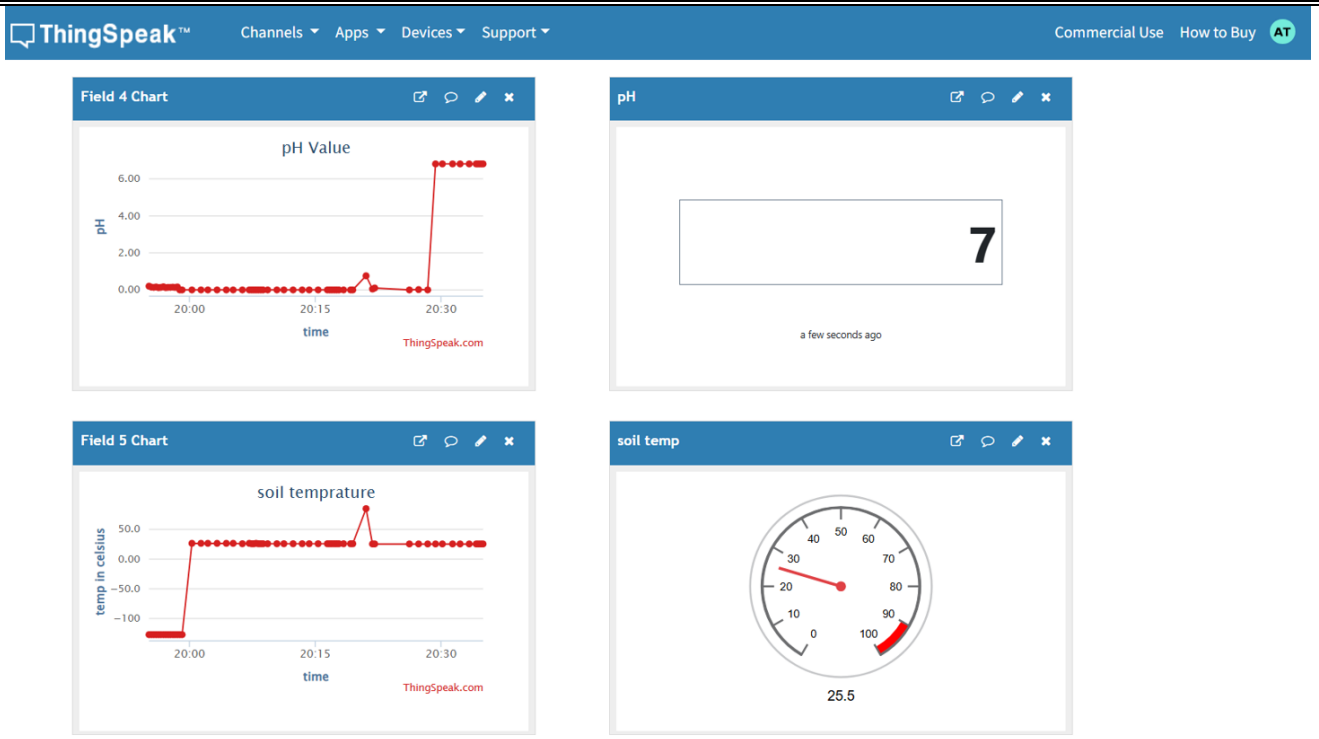


Figure 8.8: Thinkspeak Output screenshot 2

This dashboard view provides a comprehensive display of all monitored parameters (soil moisture, temperature, humidity, pH), showcasing the system's multi-sensor integration and real-time cloud reporting.

8.5 Analysis and Discussion

8.5.1. System Responsiveness

The before-and-after photos confirm the system's ability to detect and reflect changes in soil moisture promptly. The ThingSpeak outputs corroborate these findings, showing consistent data trends and successful remote transmission.

8.5.2. Data Reliability

The combination of local display and cloud-based storage ensures data redundancy and accessibility. The system's modular design and robust communication protocol minimize data loss and support scalability.

8.5.3. Practical Implications

By providing both immediate and remote access to soil and environmental data, the Soil Parameter Testing System enables informed decision-making for irrigation and soil management, supporting sustainable agricultural practices.

9

Chapter 9: Conclusion and Future Scope

9.1 Conclusion

The Soil Parameter Testing System effectively combines multiple sensors—including temperature, humidity, soil moisture, and pH—with the ESP32 microcontroller to provide real-time, multi-parameter soil monitoring. By utilizing a solar-powered battery and implementing energy-efficient duty cycling, the system is capable of autonomous operation in remote, off-grid agricultural areas, significantly reducing the need for maintenance and manual intervention. Experimental results demonstrate that the system can accurately detect and respond to changes in soil conditions, such as variations in moisture before and after irrigation, and can reliably transmit this data to both local displays and cloud platforms. The modular design of both hardware and software allows for straightforward expansion, making it easy to add additional sensors or communication modules to support a wider range of agricultural or environmental applications. Cloud integration via GSM ensures that farmers and stakeholders have remote access to real-time soil data, enabling timely, data-driven decisions for irrigation, fertilization, and crop management. Overall, the project illustrates how IoT-based solutions can bridge the gap between traditional soil testing methods and modern precision agriculture, offering a practical, scalable, and cost-effective approach to sustainable farming.

9.2 Future Scope

Recent advances in smart agriculture suggest several promising directions for extending the impact and capabilities of this system:

Automated Irrigation and Actuation:

Building on real-time soil moisture and pH data, the next step is to integrate smart actuators (such as solenoid valves or smart sprinklers) that can automatically trigger irrigation or fertilization events when soil conditions cross defined thresholds. This closed-loop automation, already being piloted in leading-edge farms, can dramatically reduce water waste and labor costs.

Edge Computing and Machine Learning:

Incorporating lightweight machine learning algorithms on the ESP32 or similar microcontrollers can enable local anomaly detection, predictive analytics, and adaptive control strategies. For example, the system could learn optimal irrigation schedules based on historical soil and weather data, or detect early signs of plant stress.

Scalable, Low-Power Wireless Communication:

Expanding beyond GSM, future deployments could leverage LPWAN technologies such

as LoRaWAN or NB-IoT for even lower power consumption and greater communication range, supporting large-scale sensor networks across extensive agricultural fields.

Multi-Depth and Multi-Parameter Sensing:

Deploying sensor arrays at different soil depths would provide a more comprehensive profile of the root zone environment, supporting precision irrigation and fertilization strategies tailored to specific crops and soil layers.

Integration with Remote Sensing and Robotics:

Combining in-situ sensor data with satellite or drone-based remote sensing can enhance spatial coverage and provide cross-validation for soil moisture and nutrient maps. Additionally, integrating with autonomous robots or UAVs can enable targeted sampling, variable-rate input application, and rapid response to detected anomalies.

User-Centric Data Visualization and Advisory Services:

Developing more intuitive mobile or web dashboards, real-time alerts, and decision-support tools will empower farmers to act on sensor data efficiently, even from remote locations. Cloud-based analytics and historical data tracking can further enhance long-term soil health management.

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